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CAMERON D. OVEY
CAMBRIDGE

MARY SEARS
WOODS HOLE, MASS.

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I. GENERAL

1. Papers should be submitted to the Editor for the appropriate country. Papers submitted for publication will naturally be judged from the standpoint of scientific originality and novelty. Technical details of apparatus used in scientific investigation can, however, be presented in brief notes. The preparation of progress reports and review articles will be invited by the Editors from time to time and it is therefore requested that no uninvited contributions of this nature be submitted. The journal will appear quarterly, four issues making up one volume.

2. Only papers that have not been previously published will be accepted for publication in *Deep-Sea Research*.

3. Authors will receive 50 free reprints of their papers. Additional copies can be purchased if ordered at the time the first proofs are returned.

II. MANUSCRIPT REQUIREMENTS

1. Manuscripts should be typewritten. The text must be ready for printing and should be carefully checked for errors. Authors will receive proofs for correction.

2. Half-tone illustrations are to be restricted to the minimum necessary. They should accompany the manuscript mounted on separate sheets. Line drawings should include all relevant details and it is particularly requested that originals and not photo-prints should be sent. Photographs should be enlarged sufficiently to permit their clear reproduction in half-tone. If words or numbers appear in photographs, two copies are requested, one clearly printed and the other without inscription. Illustrations should be made to fit within the type area after reduction, where at all possible.

3. References to published literature should be quoted in the text as follows: SMITH (1950) – the date of publication, parentheses, following the author's name. References should be listed together at the end of each paper and not given as footnotes. They should be arranged in alphabetical order (first author's surname) to appear as follows :—

BULLARD, E. C. (1954), Heat-flow through the floor of the ocean. *Deep-Sea Res.*, **1**, 65-66.

PETTERSSON, H. and ROTSCHI, H. (1952), The nickel-content of deep-sea deposits. *Geochim. et. Cosmochim. Acta*, **2**, 81-90.

It is particularly requested that (*a*) author's initials, (*b*) title of the paper and (*c*) the volume or part numbers and page numbers are given in every case.

4. The text of articles submitted should be concise and in a readily understandable style. The essential contents of each paper should be briefly recapitulated in a summary, which will appear at the head of the paper.

5. To conserve space authors are requested to mark less important portions of their papers for printing in smaller type.

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(B) denotes a book review

Deep-Sea Research, 1954, Vol. 2, pp. 1 to 23. Pergamon Press Ltd., London.

Foraminifera and deep-sea research*

By FRED B. PHLEGER

INTRODUCTION

THE Foraminifera have been of considerable value in study of certain problems of the deep sea. Sequences of planktonic species in deep-sea cores have been used to interpret stratigraphic sequences, for correlation, and to indicate possible marine conditions during glacial and interglacial times. These forms also have been used as indicators of marine water-masses, both in the modern ocean and in ancient seas. Benthonic species, used as tracers of sediment displaced from shallower into deeper water, have given considerable insight into deep-sea sedimentation. It is the purpose of this paper to summarize briefly our knowledge of the uses of Foraminifera in these and related problems, and generally attempt to evaluate the status of this phase of deep-sea research. There is no attempt to make this a complete discussion of the subject ; references are cited to illustrate the topics of discussion, and any omissions are not intended to imply criticisms of such work.

Foraminifera are marine Protozoa which may be either planktonic or benthonic in habitat, and live in all marine and semi-marine enviroments, from brackish marshes to the deep-sea. From an ecologic point of view they appear to constitute a dynamic series of populations which are constantly adapting themselves to marine environments. There is considerable morphologic variation giving rise to a large number of species and variants. The number of benthonic species is much greater than that of planktonic species, and this may be due in part to greater variation in the benthonic environments. The importance of Foraminifera in the study of marine sediment is that they produce a shell, or test, which becomes a part of the sediment when the animal dies or reproduces. The accumulation of these tests thus leaves a record in the sediment of the marine conditions in which these animals lived.

Accumulations of foraminiferal tests in deep-sea sediments are composed almost exclusively of planktonic species, with benthonic forms generally constituting only a small fraction of one percent of the total population. This planktonic population is dominated by *Globigerina*, *Globorotalia*, and their relatives, and in high concentration may be referred to as *Globigerina* Ooze. Planktonic species must be considered separately from benthonic types in any study of environment of deposition, since they represent different habitats and thus different environments. The following discussion is confined to planktonic Foraminifera except where indicated. The usefulness of Foraminifera in solving problems connected with the deep-sea is dependent upon a knowledge of their ecology, and much of the following discussion concerns what is known about modern distributions and methods of their study.

METHOD OF STUDY

Most studies of modern planktonic Foraminifera have been based on their occurrence

* Contribution No. 18, Marine Foraminifera Laboratory ; Contribution No. 719, Scripps Institution of Oceanography.

in marine sediments, but some have been made on plankton tows. In taking plankton tows for this purpose it is advisable to use relatively fine-mesh bolting silk (nominal opening 0.203 or 0.158 mm), since the smaller forms may be lost in the coarser nets normally used for zooplankton tows. Samples should be preserved in formalin which is made basic by the addition of sodium carbonate, sodium borate, or hexamethylenetetramine. This is necessary to prevent solution of the tests of the planktonic Foraminifera, all of which are composed of calcium carbonate. The Clarke-Bumpus plankton-sampler (1950) has been used extensively to sample the plankton quantitatively at known depths, and the Nansen closing net also has been used. Recently, members of the Marine Foraminifera Laboratory have done extensive sampling of the upper 50-100 m. of water by vertical tows with a small, open-mouth net. None of these methods of collection gives a completely accurate quantitative picture of the distribution of planktonic Foraminifera in the water-masses where they live. Use of a fine-mesh net inhibits free flow of sea water through the sampler, so that the population obtained may be somewhat smaller than the actual population living in the water. Calculations of the amount of water strained under such circumstances may only be approximations. Actual measure of the amount of water strained with a meter wheel, as in the Clarke-Bumpus sampler, is only a relative measure because of the difficulty of calibration. In sampling deep layers the actual depth and pattern of towing is not known certainly ; depths are estimated by angle of the towing wire at the surface.

The modern assemblage of Foraminifera is accumulating in the surface sediment except where it is being destroyed by solution of calcium carbonate or where physical processes prevent accumulation. It is assumed that the fauna in a sediment lived in the water directly above and that the specimens sink immediately upon death or reproduction. Neither of these assumptions is strictly true, in all probability, but they appear to represent reasonable approximations.

It is desirable to obtain the actual surface of the sediment to sample properly the modern fauna. This can be done easily in deep water only by means of a small coring tube which may be handled vertically on shipboard so that the undisturbed sediment may be taken from the core. Such an instrument is described by PHLEGER (1951b) and several modifications of this gear are now in use. Other advantages of using the coring-tube principle in collecting such material is that a known area is sampled, and a measured thickness can be obtained. The samples thus lend themselves to quantitative studies. Snapper samples or mixed dredge samples in general are not reliable for making quantitative faunal studies of the modern population from sediments. Surface samples from long cores generally are mixed with deeper material due to the necessity of handling cores horizontally aboard ship.

DISTRIBUTION OF LIVING PLANKTONIC FORAMINIFERA

Real knowledge of the ecology of planktonic Foraminifera should be based, in large part, on understanding their distributions within the plankton. Only a few studies have been made of the distribution of living planktonic Foraminifera from plankton tows. Early work established that there are approximately 20 or 30 planktonic species based on their presence in plankton tows. More recently, quantitative studies have been made in the Atlantic by SCHOTT (1935), by PHLEGER (1945), and in the Gulf of Mexico by PHLEGER (1951b), and work is in progress on several

hundred plankton tows which have been collected from the Pacific by J. S. Bradshaw and others at the Scripps Institution of Oceanography. Studies which have been made are too few and incomplete to solve any problems of distribution of these forms, but some interesting generalizations may be made on the data which are available.

It appears that the largest populations of planktonic Foraminifera live in the upper layers of water. Schott (1935) obtained several hundred specimens per tow from the upper 100 m. and many more, on the average, than he collected from greater depths. Phleger (1951b) found an average population of 5-6 per cubic meter of water in the upper 50 meters in the northwest Gulf of Mexico. At some stations, however, there were patches of higher concentration, up to 73 living specimens per cubic meter of water.

Live planktonic Foraminifra have been discovered at all depths which have been sampled. At a few stations larger live populations have been collected from depths greater than 100 m than from shallower layers of water. Living specimens also have been indentified from sediment samples collected with the short coring tube described above (Phleger, 1951b, p. 69 ; Parker, 1954). These specimens either were living on the bottom or in the 15-20 cm of water directly above the bottom which is collected with this sampling device. These data certainly suggest that while planktonic Foraminifera appear to be most abundant in the upper water layers they do live throughout the water column all the way to the bottom. It is possible that they may live parts of their lives at different depths. The methods used at the Marine Foraminifera Laboratory in identifying live specimens employ the recognition of protoplasm in specimens which were preserved in formalin ; the biuret colour test for protein has been used by Phleger (1951b, p. 6), and Parker (1954) has used the rose bengal stain described by Walton (1952). It is possible that many of the forms collected from deeper layers were in a resting state and were not actively growing and reproducing at those depths. The abundance of young, thin-shelled specimens in all deep-water samples, however, suggests that some growth may occur in the deeper layers.

Most plankton samples seen by the writer contain empty tests of Foraminifera, as well as those having protoplasm. These may be somewhat more abundant at greater depths, but they also occur in abundance at some places in the shoal layers of water. This suggests that these forms do not sink immediately when the protoplasm disappears from the tests. It is unlikely that these empty tests had died or reproduced immediately before collection of the samples, otherwise the population would have survived for only a very short time. It is the opinion of the writer that these abundant empty tests are evidence that some mechanism is retarding sinking to the bottom. Turbulence in the seasonal water layer could be effective in preventing these tests from sinking for some time, especially during times of deep mixing caused by high wind. Deeper turbulence, while less effective, may also retard such deposition on the bottom.

The significance of these meagre data on distribution of planktonic Foraminifera in their natural habitat suggests that certain qualifications should be kept in mind in evaluating accumulations in marine sediment, as follows :

1. The fauna in a sediment may represent environmental conditions which existed throughout the entire water column, from the surface layer to the bottom. There may be several populations living in different depth environments, or the same population may be variously affected by environments at various depths. The

principal ecological effect, however, may be from the surface water layer. It may be possible to reconstruct conditions in the entire water column if we obtain sufficiently detailed understanding of the ecology of these organisms.

2. Planktonic Foraminifera do not sink immediately, depending upon water turbulence conditions, and may be deposited at some distance from where they actually lived. The distance of such transport cannot be established at the present time and must be variable.

DISTRIBUTION OF PLANKTONIC FORAMINIFERA IN SEDIMENT SAMPLES

Most of the information on the distribution of planktonic Foraminifera is based on their occurrence in sediment samples. Much of the early work on distributions was qualitative and was on sediment samples collected by methods whose reliability is questionable inasmuch as many pre-modern materials were obtained and the amount of sample used was variable. SCHOTT (1935) has given excellent quantitative data

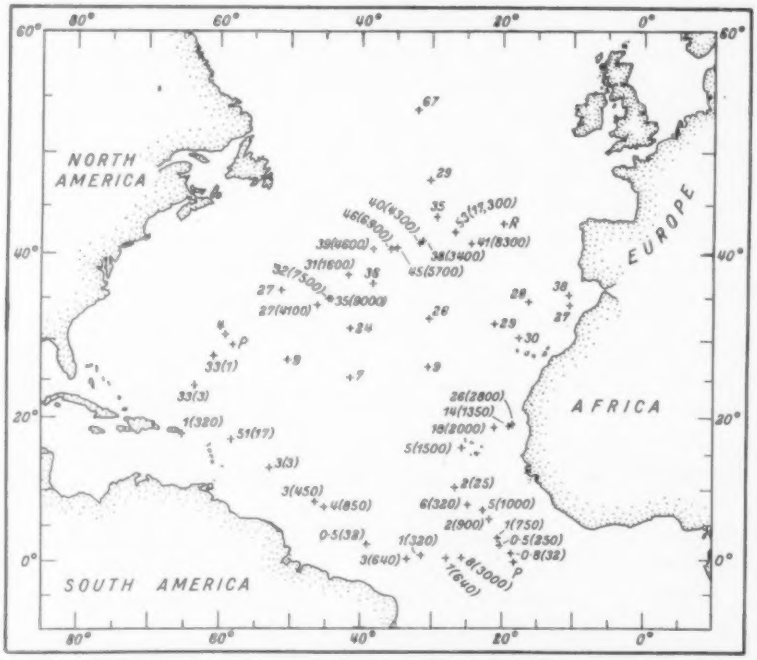


Fig. 1. Distribution of *Globigerina bulloides* d'Orbigny in surface sediment samples from the Atlantic. First number at each station is per cent of total population of planktonic Foraminifera; second number, in parentheses, is estimated number of specimens. (After PHLEGER, PARKER and PEIRSON, 1953).

on the distribution of species in samples collected by the *Deutsche Atlantische Expedition* in low-latitude areas of the Atlantic. OVEY (in WISEMAN and OVEY, 1950, p. 59, table 1) has listed species characteristic of Arctic and Antarctic, temperate, and warm water based on quantitative study of nine samples from the Atlantic.

More recently PHLEGER, PARKER and PEIRSON (1953) have listed generalized distributions in the North Atlantic based on the study of approximately 50 sediment samples in mid and low latitudes. The types of distributions listed by them are

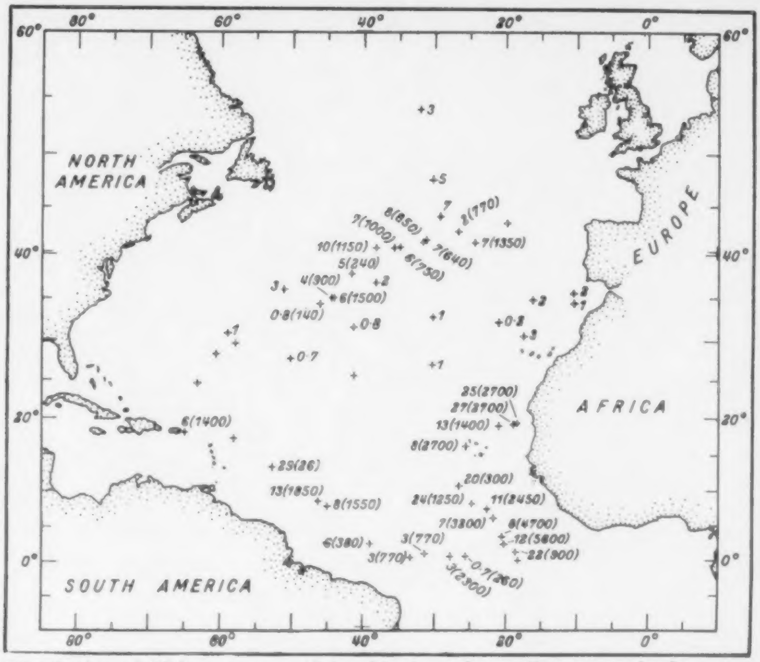


Fig. 2. Distribution of *Globigerina eggeri* Rhumbler in surface sediment samples from the Atlantic. First number at each station is per cent of total population of planktonic Foraminifera ; second number, in parentheses, is estimated number of specimens. (After PHLEGER, PARKER and PEIRSON, 1953).

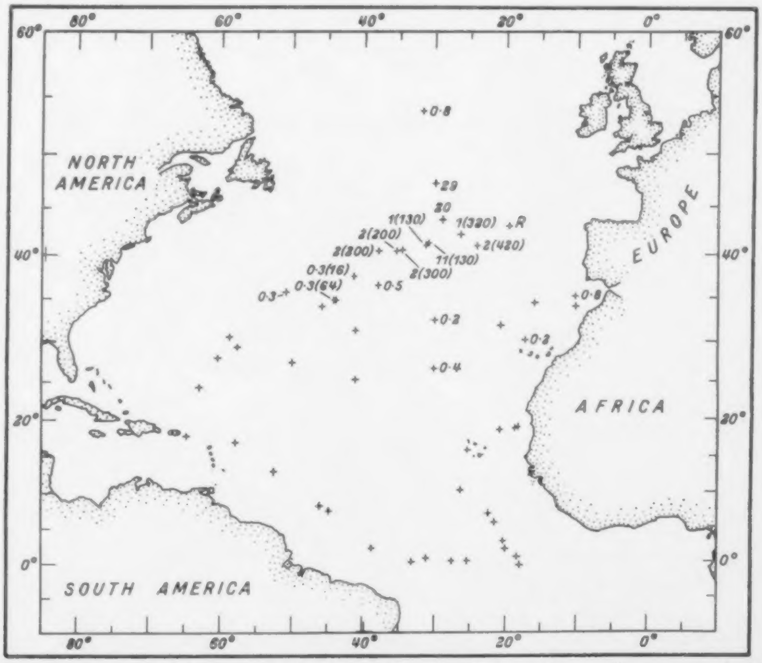


Fig. 3. Distribution of *Globigerina pachyderma* (Ehrenberg) in surface sediment samples from the Atlantic. First number at each station is per cent of total population of planktonic Foraminifera ; second number, in parentheses, is estimated number of specimens. (After PHLEGER, PARKER and PEIRSON, 1953).

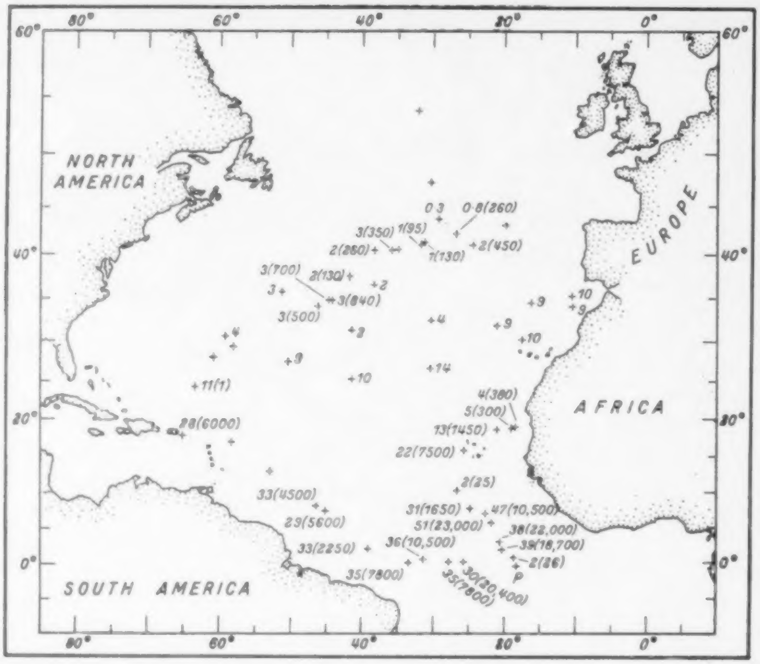


Fig. 4. Distribution of *Globigerinoides sacculifera* (H. B. Brady) in surface sediment samples from the Atlantic. First number at each station is per cent to total population of planktonic Foraminifera; second number in parentheses, is estimated number of specimens. (After PHLEGER, PARKER and PEIRSON, 1953).

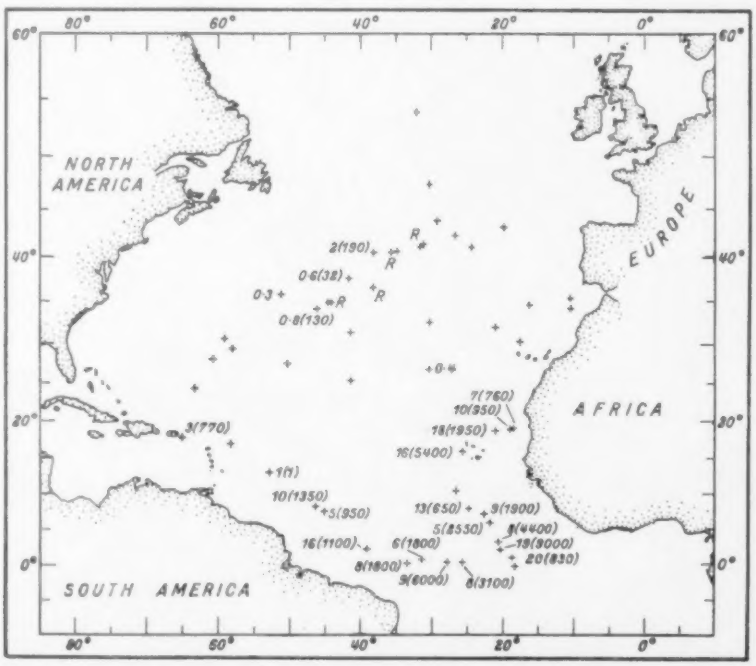


Fig. 5. Distribution of *Globorotalia menardii* (d'Orbigny) in surface sediment samples from the Atlantic. First number at each station is per cent of total population of planktonic Foraminifera ; second number, in parentheses, is estimated number of specimens. (After PHLEGER, PARKER and PEIRSON, 1953).

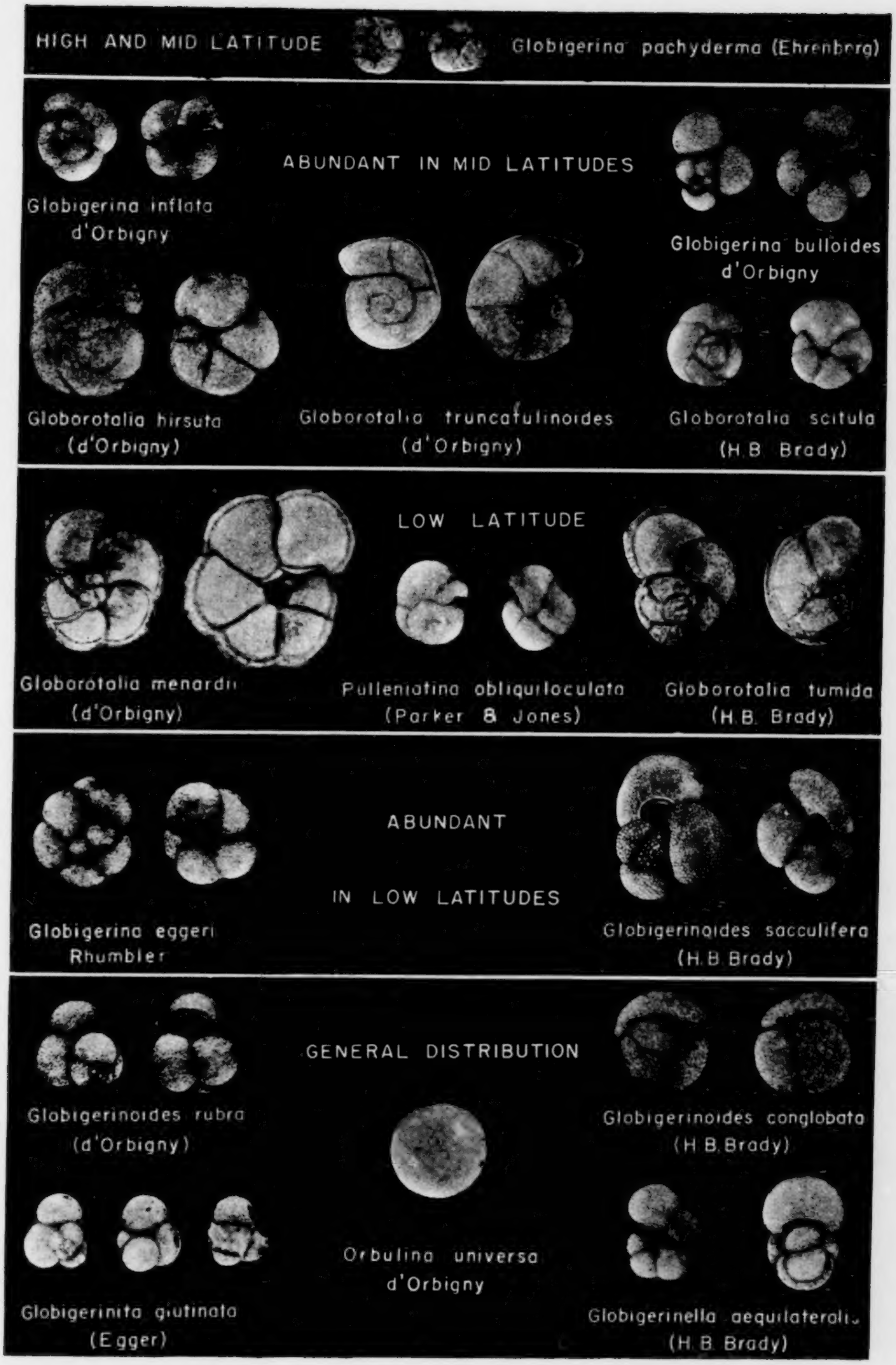


Plate 1. Species of common North Atlantic Foraminifera arranged according to types of distribution.

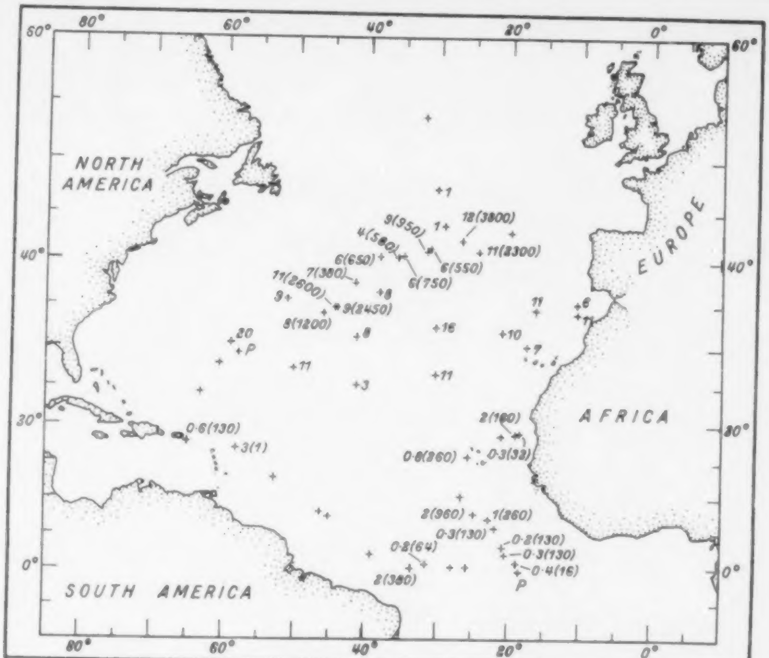


Fig. 6. Distribution of *Globorotalia truncatulionoides* d'Orbigny in surface sediment samples from the Atlantic. First number at each station is per cent of total population of planktonic Foraminifera ; second number, in parentheses, is estimated number of specimens. (After PHLEGER, PARKER and PEIRSON, 1953).

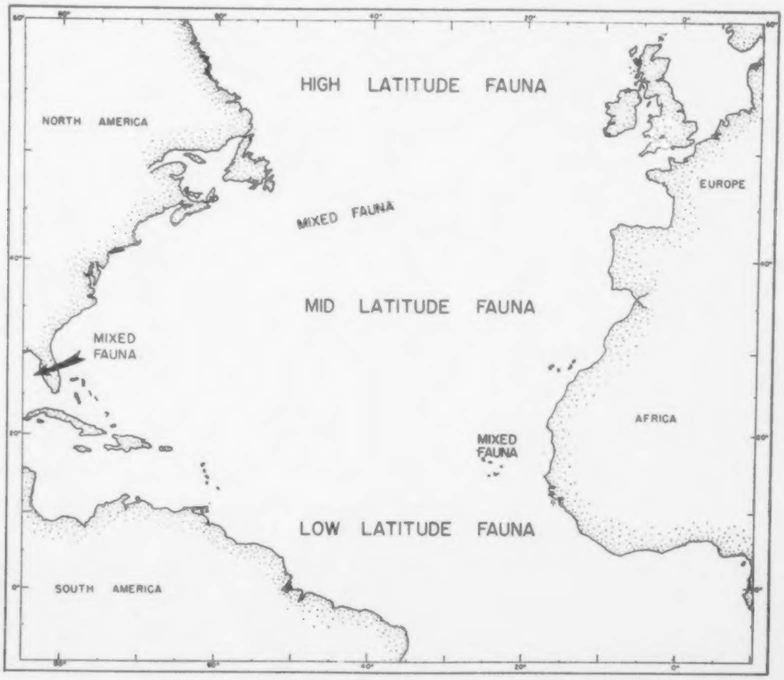


Fig. 7. Generalized facies of planktonic Foraminifera in North Atlantic.

believed to represent as good a generalization as can be made at the present time, but it must be realized that these are based on very few samples from so large an area, except for the tropical region covered by SCHOTT (1935). The distributions listed by PHLEGER *et al.* (1953, p. 71) are as follows (see Plate 1 for illustrations of the species) :

" 1. The following species seem to be characteristic of low latitudes, less than 20° N. Lat., where they occur in relatively high frequencies ; they also occur in low frequencies at a few stations in mid-latitudes in the central Atlantic :

Globorotalia menardii (d'Orbigny)
G. tumida (H. B. Brady)
Pulleniatina obliquiloculata (Parker and Jones)

2. The following species occur in much greater abundance in low latitudes, although they occur at most of the stations (studied by the authors) :

Globigerina eggeri Rhumbler
Globigerinoides sacculifera (H. B. Brady)

3. *Globigerina pachyderma* (Ehrenberg) is confined to high and mid-latitudes.

4. The following species are more abundant in mid-latitudes although they also occur (in much lower frequencies) in low latitudes :

Globigerina bulloides d'Orbigny
G. inflata d'Orbigny
Globorotalia hirsuta (d'Orbigny)
G. scitula (H. B. Brady)
G. truncatulinoides (d'Orbigny)

5. The following species are universally distributed in approximately uniform frequencies within the area covered in this report :

Globigerinella aequilateralis (H. B. Brady)
Globigerinita glutinata (Egger)
Globigerinoides conglobata (H. B. Brady)
G. rubra (d'Orbigny)
Orbulina universa d'Orbigny

These data, and also data from OVEY (in WISEMAN and OVEY, 1950 and SCHOTT 1935) seem to establish clearly what may be termed high-latitude, mid-latitude, and low-latitude faunas in the North Atlantic. Occurrences of a few species characteristic of these distributions are shown in Figs. 1 to 6. It is presumed that similar geographic faunas also occur in the Pacific, but the reliable data are too few in that region to make any generalization.

These distributions have been attributed to the ecological effect of surface ocean temperature by many workers, but there is no good evidence of this. This conclusion is based largely on the occurrence of different faunas in areas where different surface surface temperatures occur, and the fact that temperature is an important factor in affecting distributions of other organisms. It does not seem valid to consider that temperature is the only important ecologic factor affecting these distributions. Other factors which are of possible ecologic importance are salinity, nature and amount of food, water chemistry such as trace elements, pH and eH, depth, hydrostatic pressure (see OPPENHEIMER and ZOBELL, 1952), turbidity, turbulence, substrate

(if there is a benthonic stage), currents, biologic competetion, predators, disease, etc. Physiological experimentation will be necessary to determine the relative importance of these various factors. Preliminary experiments on benthonic types, such as the frequently cited work of MYERS (1935a, 1935b, 1936, 1937, 1943) do not necessarily have much application to these problems. His studies are mostly confined to benthonic Foraminifera, and studies on one species or even the fauna from one environment do not necessarily apply to another species or another environment. It seems probable that an infinite amount of study and experimentation must precede any real understanding of the effects of various enviromental factors on species and faunas of Foraminifera.

The writer recently has adopted a generalization which seems to aid in explaining the distributions of some of these faunas. This is the ecologic water-mass, based in part on a common concept in physical oceanography in which various marine water-masses are differentiated by some of their physical characteristics. An ecologic water-mass may be defined as any body of marine water which has a uniform ecologic effect and supports a uniform assemblage of organisms. On this basis it may be said that the three geographic foraminiferal faunas in the North Atlantic are differentiated because they inhabit and are adapted to three different water-masses. This is essentially true in the sense of physical oceanography and it appears reasonable from an ecological point of view.

MIXED PLANKTONIC FAUNAS

Mixing of planktonic faunas is expected to occur wherever there is mixing of the different water-masses which these different faunas inhabit. One of the most obvious examples of this is the transport of the low-latitude species, such as *Globorotalia menardii* (d'Obigny), into mid-latitudes by the Gulf Stream System (see figure 5). The transport of warm water into mid and high latitudes by this mechanism is well-known. Occasional masses detach themselves from the Gulf Stream and invade far beyond what appears to be the normal path of the currents. The presence of such low-latitude species as *Globorotalia menardii* (d'Orbigny) and *Globigerinoides sacculifera* (H. B. Brady) in the southern Gulf of Maine (PEIRSON, personal communication) undoubtedly is the result of such a mechanism. Occurrence of similar low-latitude species in pre-modern sediments, presumably Pleistocene in age, under Boston Harbor suggests that this mechanism has been occurring for some time (PHLEGER, 1949 ; STETSON and PARKER, 1942).

The Gulf Stream is bounded on the north by sub-Arctic water. The position of this boundary is known to shift through a considerable distance and there is mixing of the two water-masses in the boundary area. The sediments underlying this region contain a mixed high and mid-latitude fauna with some low-latitude species in low frequencies. A sample reported by PHLEGER and HAMILTON (1946, plate 1) from this boundary region near Georges Bank contains the following species in relative abundance :

Globigerina eggeri Rhumbler (low-latitude)
G. inflata d'Orbigny (mid-latitude)
G. pachyderma (Ehrenberg) (high-latitude)
Globigerinoides rubra (d'Orbigny) (low and mid-latitude)
Globorotalia menardii (d'Orbigny) (low-latitude)

Other samples in the collections of the Marine Foraminifera Laboratory from this general area have a similar faunal composition. Such a natural mixture of these faunal elements could only occur at the position of the Arctic or Antarctic convergence ; low-latitude species are expected to be more abundant on the upstream side of the warm-water current in such a convergence area.

Figure 1 shows a high concentration of *Globigerina bulloides* d'Orbigny, a typical mid-latitude species, at a few stations off the west coast of Africa between Cape Verde and Cape Blanco. Fig. 5 shows a high frequency of *Globorotalia menardii* (d'Orbigny), a low-latitude form, at the same stations. The occurrence of these two species together in high frequencies is an apparently anomalous association. These mixed assemblages occur in the area of the Equatorial Counter Current and in general where it combines with water from the Canaries Current to form the North Equatorial Current. This also is the position of the North-east Trade Winds, which provide most of the force moving the North Equatorial Current. It is believed that these mixed faunas occur because the low-latitude forms are being contributed from the Counter Current water and the mid-latitude forms are from the mid-latitude water of the Canaries Current. Mixed faunas in these latitudes are expected to occur only on the eastern sides of oceans in a convergence area. There is a water divergence on the opposite side of the North Atlantic and a pure low-latitude fauna is expected.

Distributions of several species of planktonic Foraminifera in the northern Gulf of Mexico are shown on Figs. 8 to 13. These distributions are based on occurrences in more than 700 surface sediment samples from this region and are believed to give an accurate general picture of occurrences. These may be compared with the distributions of the same species in the North Atlantic on Figs. 1 to 6. It is seen that the Gulf of Mexico fauna is a mixed low-latitude and mid-latitude one. An illustration of the mixed nature of this fauna is the association of the following species in relatively high frequencies : *Globigerina bulloides* d'Orbigny, *G. eggeri* Rhumbler, *Globigerinoides sacculifera* (H. B. Brady), *Globorotalia menardii* (d'Orbigny), *G. truncatulinoides* (d'Orbigny), and *Pulleniatina obliquiloculata* (Parker and Jones). This is interesting, inasmuch as most or all of the water apparently being supplied to the Gulf of Mexico appears to be from the North Equatorial Current system and should contain a pure low-latitude fauna. It is expected that the Gulf of Mexico should be populated with this assemblage. The writer suggests two possible explanations for the presence of the mixed fauna : (1) Mid-latitude water carrying its indigenous planktonic fauna may enter the Gulf of Mexico around the Florida Peninsula. It is possible that this water enters and is dispersed by a coastal current system flowing west and northwest. (2) The mid-latitude fauna may have invaded this region during one of the Pleistocene glacial stages, or at some other time in the past, and may now be a " relict " fauna.

Further examination of the distribution (Figs. 8 to 13) shows two types of distribution in the northern Gulf of Mexico. *Globigerina eggeri* Rhumbler, *Globigerinoides sacculifera* (H. B. Brady), and *Globorotalia menardii* (d'Orbigny) generally occur in highest frequencies in the southeast part of the area, opposite Yucatan Strait where the tropical water-mass enters the Gulf of Mexico. The frequencies of these species generally decrease toward the northwest. This suggests that the Gulf of Mexico is being stocked with these three species as a result of their being introduced with the low-latitude water-mass which they inhabit. These low-latitude species would

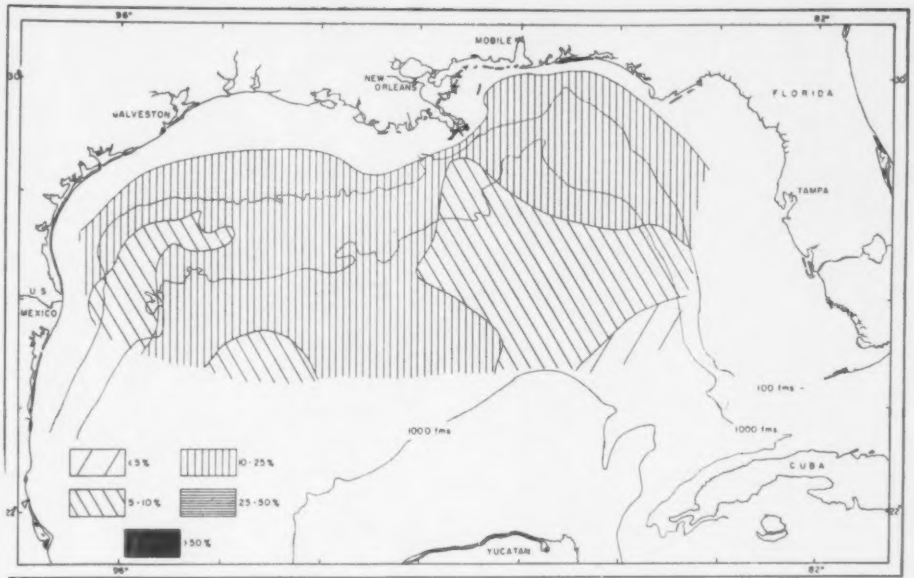


Fig. 8. Distribution of *Globigerina bulloides* d'Orbigny in northern Gulf of Mexico in per cent of total population of planktonic Foraminifera. (Based on data from PHLEGER, 1951b, and PARKER, 1954).

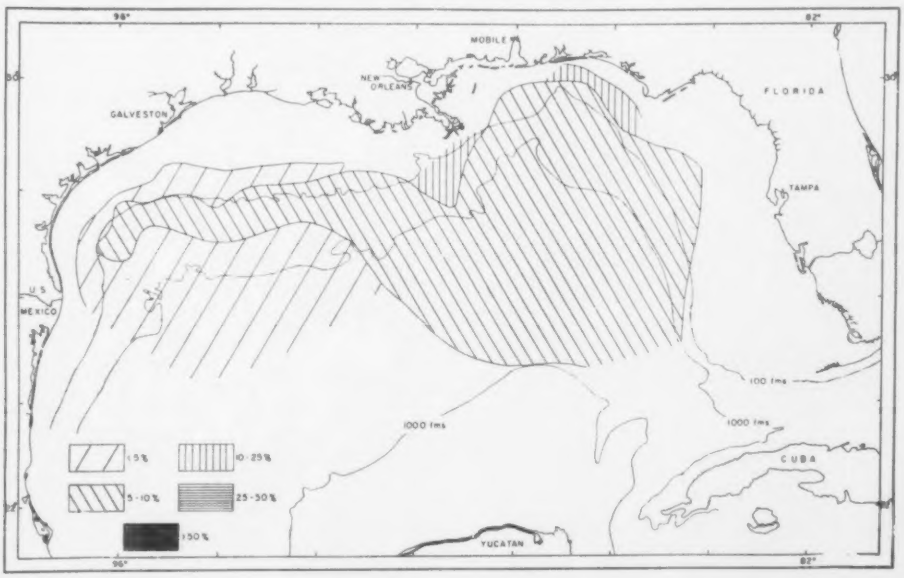


Fig. 9. Distribution of *Globigerina eggeri* Rhumbler in northern Gulf of Mexico in per cent of total population of planktonic Foraminifera. (Based on data from PHLEGER, 1951b and PARKER, 1954).

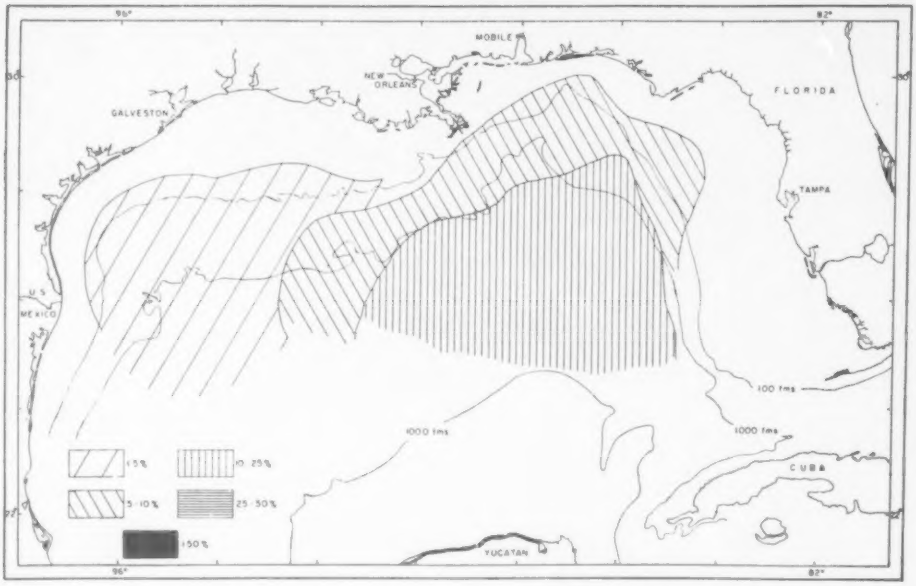


Fig. 10. Distribution of *Globigerinoides sacculifera* (H. B. Brady) in northern Gulf of Mexico in per cent of total population of planktonic Foraminifera. (Based on data from PHLEGER, 1951b, and PARKER, 1954).

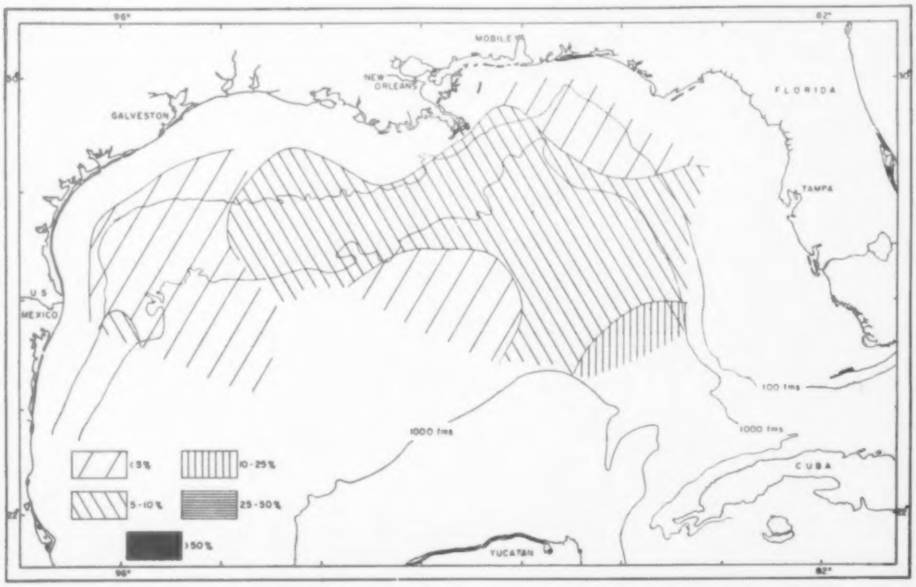


Fig. 11. Distribution of *Globorotalia menardii* (d'Orbigny) in northern Gulf of Mexico in per cent total population of planktonic Foraminifera. (Based on data from PHLEGER, 1951b, and PARKER, 1954).

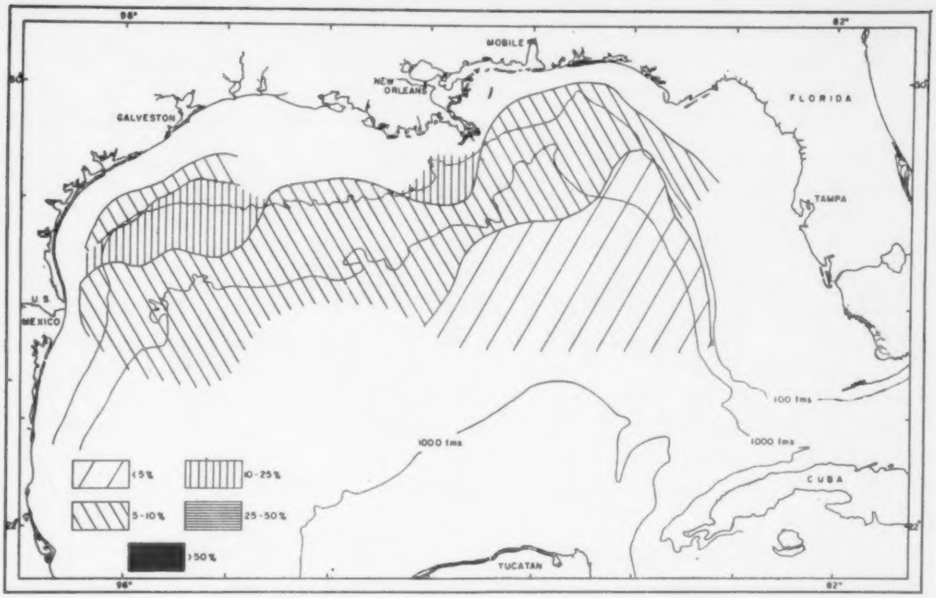


Fig. 12. Distribution of *Globorotalia truncatulinoides* (d'Orbigny) in northern Gulf of Mexico in per cent of total population of planktonic Foraminifera. (Based on data from PHLEGER, 1951b, and PARKER, 1954).

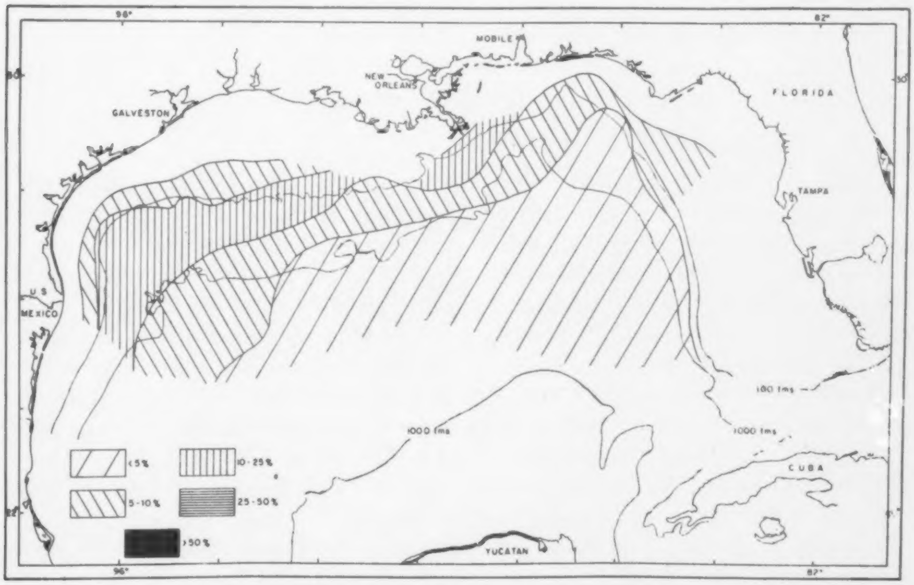


Fig. 13. Distribution of *Pulleniatina obliquiloculata* (Parker and Jones) in northern Gulf of Mexico in per cent of total population of planktonic Foraminifera. (Based on data from PHLEGER, 1951b, and PARKER, 1954).

probably be of uniformly high frequencies in the region if low-latitude water filled the entire area of the basin.

The characteristically mid-latitude species, *Globigerina bulloides* d'Orbigny and *Globorotalia truncatulinoides* (d'Orbigny), are more abundant in the north-westernmost Gulf of Mexico and decrease in frequency toward the east and south. The centre of highest frequency does not appear to be related to any immediate source of mid-latitude water from the Atlantic. It is possible that these species were introduced into the Gulf of Mexico in abundance during some earlier time when mid-latitude water may have been abundantly supplied to the basin. They may have been able to survive and reproduce in abundance because the northwest Gulf of Mexico assumes characteristics of mid-latitude water during the winter season. The distribution of the low-latitude and mid-latitude species suggests that the water in the northwest behaves as a separate mass. This is in agreement with a suggestion made by R. C. REID (personal communication) that the water circulation in the western Gulf of Mexico is in the form of a large eddy and that there may be little communication with the water in the eastern part of the basin. It is apparent from the distributions of the planktonic Foraminifera that some water interchange occurs, but it may be relatively small.

Pulleniatina obliquiloculata (PARKER and JONES) is a low-latitude species which occurs in the area immediately north of the Yucatan Strait (Fig. 13) in frequencies similar to those in the North Atlantic. It is more abundant, however, in the northwest Gulf of Mexico, constituting up to 25% or more of the planktonic Foraminifera at numerous stations. These data also suggest that this species became established in this area during previous conditions. It is suggested that *P. obliquiloculata* (Parker and Jones), *Globigerina bulloides* d'Orbigny, and *Globorotalia truncatulinoides* (d'Orbigny) may be in part relict in the northwest Gulf of Mexico.

PLANKTONIC FORAMINIFERA IN DEEP-SEA CORES

(a) *Stratigraphic Sequences*

Planktonic Foraminifera have been used by several workers to interpret the stratigraphy of deep-sea cores. It is assumed that the fauna at the top of such a core has accumulated during the present conditions obtaining at the place where the core was collected. Differences between the faunas occurring at lower levels in the core and those at the top of the core are interpreted in terms of what is known of distributions of the modern assemblages discussed above. Interpretations which have been made are in terms of surface water temperatures, on the assumption that different assemblages reflect differences in these temperatures. These differences in surface water temperatures at certain times during the past have been taken to represent glacial and interglacial stages and/or substages during the Pleistocene epoch; moreover, some authors have attempted correlations of the faunal sequences with Pleistocene chronology in Europe and North America.

It is seen in the discussion above that knowledge of the environments under which various planktonic Foraminifera live and are deposited in the sediments is very incomplete. Any conclusions about conditions represented by older faunas, therefore, must be considered as approximations only. This should be realized in evaluating any generalizations based on faunal sequences in submarine cores.

It has been widely recognized that in many deep-sea cores there are one or more faunas of planktonic Foraminifera below the surface which are unlike the modern fauna and are similar to those occurring at a higher latitude than that of the core being studied. The inference that such faunas lived when the water-mass at the core location was different and like that now prevailing at a higher latitude seems to be a reasonable one. It also appears reasonable that one of the characteristics of such a higher-latitude water-mass is lower surface temperature conditions than those in a lower-latitude water-mass. These higher-latitude faunas in cores may be referred to as " colder " faunas for convenience, but it should be realized that this is essentially an empirical, descriptive term. The colder-water faunas from low-latitude cores are mid-latitude faunas and those from mid-latitudes are high-latitude faunas. Recognition of such colder-water faunas in cores from high latitudes is difficult or impossible at the present stage of our knowledge.

These colder faunas of Foraminifera have been reported from several areas. Schott (1935) recognized a higher-latitude fauna in the lower part of numerous cores collected from the tropical Atlantic. The colder fauna was distinguished principally by the absence of *Globorotalia menardii* (d'Orbigny), which is abundant in the surface samples in this region. Cushman and Henbest (1940) differentiated colder-water funas in a series of cores from approximately 50° N. Lat. in the Atlantic. Several cold-water faunas are recorded from the Atlantic continential slope of the northeastern United States by Phleger (1939, 1942), from approximately 37° N. Lat. to 41° N. Lat. Additional reports from the Atlantic are as follows : in one core from the Caribbean Sea (Phleger, 1948), in numerous cores from the northwest Gulf of Mexico (Phleger, 1951b), in several cores collected by Ericson, Ewing and Heezen (1952) from the western North Atlantic, in three cores from the equatorial Atlantic studied by Schott (1952), and in two cores from the western basin of the Atlantic at 40° N. Lat. (Phleger and Hamilton, 1946). Stubbings (1937) studied six cores containing alternating warm and cold faunas from the Arabian Sea and Phleger (1947) reports a similar sequence from the Tyrrhenian Sea. Arrhenius (1952) recognized several Pleistocene stages in the eastern equatorial Pacific based in part on sequences of planktonic Foraminifera.

(b) *Correlation of Faunas from Deep-sea Cores.*

In most of the cores studied there are sequences of alternating cold- and warm-water faunas, interpreted as reflecting glacial and interglacial stages represented on land. The problem of correlation between cores within or between different oceanic areas arises in connection with making generalizations about the marine conditions of the Pleistocene. It is difficult, and may be impossible, to correlate widely separated sequences with the present information and understanding of the problem. Bramlette *et al.* (1940) have correlated most of their cores on the basis of stratigraphic distribution of volcanic ash and marine zones. Arrhenius (1952) has correlated his core sequences in the eastern Pacific on the basis of several biological and chemical characteristics. The use of several sedimentary criteria appears to be more reliable than the use of faunas alone, but the faunal composition also should be used in such an attempt.

Phleger *et al.* (1953, p. 111) have discussed the problem of correlation in deep-sea cores by means of planktonic faunas of Foraminifera, as follows : " The species are

modern ones and although minor variations having age significance may be established with further, detailed study, there are no presently recognized extinct species or varieties in this age range (post-Miocene).... The only apparent general means of correlation of these microfaunas is by matching supposed similar events based upon faunal interpretations. It can be inferred, for example, that the uppermost ' colder-than-modern " faunas in all the cores are correlatives. Likewise, successively lower " warm "- and " cold "-water funas in the various cores have been interpreted as having been deposited at the same time. Correlation has been based, therefore, on matching a series of events which in turn are based on ecological interpretations of the microfaunas.

" The faunal variations in a core may be quite real but their significance can be questioned. The differences between low, mid, and high-latitude faunas have been correlated with the distribution of oceanic surface isotherms. This correlation is imperfect and is based upon few and relatively unreliable data. It is assumed that surface water temperatures are of primary ecologic importance, and this is not necessarily true. It is possible that some of the faunal variations may be caused by local water-mass migrations which are not necessarily of very great over-all significance." This latter suggested complication may be most pronounced in a region such as the northern edge of the Gulf Stream. It is now well-known that the position of the Gulf Stream varies considerably (ISELIN and FUGLISTER, personal communication) and also that there are eddies, counter-currents, and numerous bodies of water which have been detached from the main water-mass. Certain sequences of cold- and warm-water planktonic Foraminifera collected from this region may be suspected of reflecting such water movements.

It seems probable that the lower boundary of the modern fauna is to be correlated between cores, but only in those where this boundary can be recognized with some assurance. Also, some recent work has suggested that some variations within certain species may have a time significance. It is reported by BOLLI (1950), for example, that direction of coiling in *Globorotalia* may be of value. According to BOLLI (*op. cit.*, p. 87)" .... changes in coiling in a number of species of *Globorotalia* .... during their vertical range .... show that certain rules may govern the evolution of these species insofar as the nature of the coiling is concerned. Those specimens which coil in either direction in approximately equal numbers are usually the earlier representatives of a species .... The stratigraphically younger representatives of a species appear to change abruptly to almost entirely a sinistral or dextral coiling ... "

ERICSON (1953) has studied stratigraphic distribution of the direction of coiling of *Globorotalia truncatulinoides* (d'Orbigny) in several cores from the Atlantic. His results indicate different ratios of right and left coiling at various times during the recent past and his preliminary results show this to be a promising tool for correlation. PHLEGER *et al.* (1953) found that *Globorotalia tumida* (H. B. Brady) *s.s.* may be of some value in correlation of cores from the North Atlantic. This species appears to be no older than their last cold-water fauna in the cores where it occurs, and may thus be a guide to late glacial and post-glacial times. ERICSON has found (personal communication) that *Globorotalia tumida* (H. B. Brady) var. *flexuosa* (Koch) has a definite upper limit in many of his cores, and may be no younger than the warm-water fauna preceding the present one. The distribution of this variety has been studied in the Atlantic cores collected by the Swedish Deep-Sea Expedition, described

by PHLEGER *et al.* (*op. cit.*). We have found that the upper stratigraphic range of this variety is limited approximately to the warm fauna preceding the present one in some cores, and occurs in what is presumed to be the post-glacial faunas in others. It is possible, however, that frequency distributions of this form will be useful in future studies. All these preliminary studies suggest that consistent variations within species may prove to be of great value in future correlations of faunas in deep-sea cores.

(c) *Rate of Sedimentation*

One method of estimating the absolute rate of deep-sea sedimentation is based on the thickness of sediment which has accumulated during post-glacial time, determined on the basis of foraminiferal sequences. SCHOTT's (1939) rates were based on the assumption of 20,000 years for the length of post-glacial time and varied from 0·5 to 3·3 cm/1,000 yrs. in the Atlantic. The estimate of 20,000 years for post-glacial time may be too long, and also the ocean may not have responded to climatic changes in the same manner or at the same time as the lands ; nevertheless, this is one of the best methods available for measuring rate of deep-sea deposition.

It seems likely that relative rates of sedimentation may be estimated if time correlations between cores are possible. PHLEGER *et al.* (1953, pp. 115-116) have indicated that this may be possible in some of their mid-latitude cores between 40°N. Lat. and 50° N. Lat. These are based on the assumption that a series of events presumed to be similar may be correlated. The general observation may be made that there are apparent differences in relative sedimentation rates, that in some places this rate was very high while at other places it was extremely low, and that the sedimentation rates may vary with time.

It may eventually be possible to calculate absolute rates of deep-sea deposition of sediment using rates of production of planktonic Foraminifera. This would be based on the Foraminifera as a source of sedimentary material exclusively marine in origin and independent of materials of terrestrial origin. Such a method would require specific data on rate of production of these forms, some of which may be obtained by frequent sampling of the standing crop over a long period of time, and much of the information would be required from experimental culturing.

(d) *Generalizations to be made from Sequences of Core Foraminifera.*

The widespread occurrence of a cold fauna beneath the modern one strongly suggests that it is to be generally correlated, as discussed above. A part of this lower fauna contains elements at present adapted to higher latitudes at all places where such faunas are known and adequately reported, and thus they are presumed to represent lower surface-water temperatures. This suggests that sea-surface temperatures were generally cooler at all latitudes during the deposition of the " late-glacial " assemblages. PHLEGER (1951b, pp. 78-79) has attempted to assign approximate surface-temperature values to lower, cold-water core faunas and transition core faunas in the northwest Gulf of Mexico :

" Transition faunas (between warm and cold-water faunas) .... contain elements suggestive of the present North Atlantic continental slope region, between approximately Cape Henry and Cape Cod.

" Surface waters over the slope of the region from Cape Henry to Cape Cod have temperatures approximately as follows : maximum surface temperatures (August) range from about 77°F in the south to 65°F in the north ; minimum surface temperatures (February) range from about 60°F in the south to 45°F in the north .... The ' transition fauna ' between the upper and lower faunas in the cores may have accumulated under surface water temperature conditions similar to those given. The lower core fauna may have accumulated under somewhat colder conditions, but no so cold as in present Arctic waters."

The presence of alternating cold- and warm-water faunas suggests alternating times of relatively colder and warmer sea surface-water temperatures. Various attempts have been made to correlate these presumed cold- and warm-water conditions with stages and/or substages of the Pleistocene known in North America and in Europe. Such correlation is pure speculation based on very incomplete evidence and may be misleading. An attempt has been made by Ovey (1949, p. 230) to correlate data given by Phleger (1948) on a core from the Caribbean Sea with the Pleistocene glacial chronology and stage names of North America. This has been copied by Sigal (1952, p. 294) in his admirable section on Foraminifera in *Traité de Paléontologie*, and thus has assumed a certain reliability. The diagram used by these authors is based upon speculation by the original investigator (Phleger, 1948, pp. 7-8) which is subject to all the uncertainties discussed previously. It is probably incorrect to assign North American chronological names to such material regardless of its possible reliability or unreliability.

Mixed low-latitude and mid-latitude planktonic faunas of Foraminifera have been reported in lower samples of five deep-sea Atlantic cores by Phleger *et al.* (1953, pp. 108-109). It is shown above that similar mixed faunas occur in the eastern Atlantic at the convergence of the tropical Counter Current and the mid-latitude water of the Canaries Current system in the eastern Atlantic at the position of the North-east Trades at 20-25°N. Lat. The lower mixed faunas in the cores are also from the eastern Atlantic, but occur at 0-7° N. Lat. " These data strongly suggest that at some time during the past the convergence area has shifted southward at least 10 or 15° of latitude. If this suggested interpretation is correct, then the position of the North Equatorial Current and also the Trade Winds belt may also have shifted southward by this amount at some times during the past.

" The implications of this southward shift of the Trade Winds and current system are of considerable interest. It may be presumed that these faunas represent a cold-water phase and some glacial stage of the Pleistocene. It may suggest that the northern hemisphere mid and low-latitude wind belts were displaced toward the southern hemisphere during the Pleistocene, or it may indicate a telescoping of the wind circulation in equatorial regions. The effect of such a modification of the wind system would be expected to have far-reaching effects on the Atlantic water circulation and therefore far-reaching effects on continental climates." (Phleger *et al.*, *op. cit.*, p. 120).

Arrhenius (1950, p. 87) in connection with his work on deep-sea cores from the eastern Pacific states : " The results from the investigations of the east Pacific sequences .... indicate great constancy in the path of the Counter Current during Pleistocene time .... The lack of significant displacements of the Counter Current during Pleistocene time appears to be a definite proof that the climatic changes were

synchronous in the northern and southern hemispheres." It is apparent from these conflicting conclusions that more study is required on this interesting phase of deep-sea research.

DISPLACED FAUNAS AND THEIR IMPLICATIONS

The occurrence of sands in occasional deep-sea deposits has been recognized by several people but only in recent years has the significance of these deposits been appreciated. It is well-known that coarse-grained sediments, i.e. sands, are generally characteristic of nearshore deposits. Their occasional presence in deep water could mean : (1) that they were deposited in shallow water and have been displaced into deep water, (2) that they were deposited when the deep-sea areas in which they are found were much shallower, or (3) that there are unknown processes in the deep-sea which act to produce occasional deposits of sand.

Benthonic Foraminifera have proved to be of great value in studying the origin of these deep-sea sands in proving that such sands have been displaced from shallow into deep water. The depth displacement of these forms is based on what is known of depth distributions of benthonic Foraminifera, based on studies such as those by Natland (1933), Parker (1948), Colom (1952), Lowman (1949), Phleger (1942, 1951a), and Walton (1954). Tests of Foraminifera may be considered an integral part of their enclosing sediment and where the material is displaced out of its normal depth-habitat the Foraminifera constitute at present the most reliable record of its former environment.

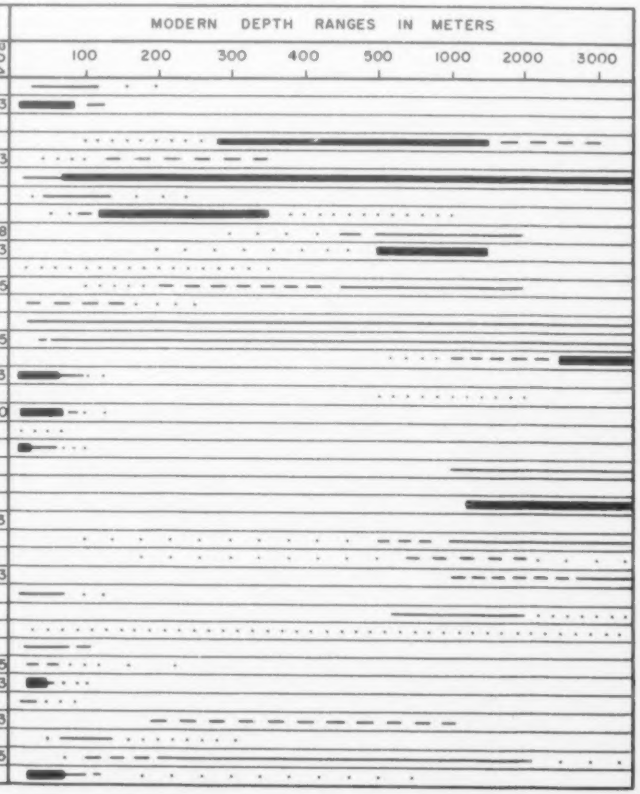
The displaced faunas recorded in two cores collected from the Sigsbee Deep in the Gulf of Mexico may be cited as an example of these displaced microfaunas. The data on these faunas are listed by Phleger (1951a, fig. 31 ; 1951b, fig. 7) ; Table 1 shows some of these data along with known depth distributions of all the benthonic species occurring in the cores and from the same area. An examination of Table 1 shows rather striking differences between the benthonic assemblage in the upper parts of cores 335 and 336 from the Gulf of Mexico and in the lower parts of the cores. The upper fauna is almost exclusively composed of the following : *Cibicides wuellerstorfi* (Schwager), *Eggerella bradyi* (Cushman), *Epistominella decorata* (Phleger and Parker), *Eponides polius* (Phleger and Parker), *E. tumidulus* (H. B. Brady), *Glomospira charoides* (Jones and Parker), and *Nonion pompilioides* (Fichtel and Moll). These forms characterize the normal assemblage in this area at depths greater than 2,000 m, as seen by examining the range-chart, and the fauna is normal for the depth at which it was collected. The lower core fauna, on the other hand, contains species which normally occur at a variety of depths, and many of which are from depths shallower than approximately 100 m. This demonstrates that such species, from depth-ranges shallower than 2,000 m, and their enclosing sediment have been displaced downslope from their normal habitat. The presence of deep-water forms, along with shallow-water species, is evidence that the material was deposited at about the same depth at which it now occurs. The shortest distance to a depth of 100 m is approximately 80 nautical miles.

Several displaced faunas of benthonic Foraminifera are recorded by Phleger *et al.* (1953) from the North Atlantic from near the Canary Islands, near the Cape Verde Islands, and near St. Croix, all areas of known high submarine relief. Two cores off the coast of Brazil at 4,500 m depth have thick sections containing shallow-

Table 1

Foraminifera in selected samples from cores 335 and 336, northwest Gulf of Mexico in per cent of total population of benthonic Foraminifera. (After PHLEGER, 1951a).

	CORE 335 - 3438 m.													CORE 336 - 3530 m.									
Cm. from top of core	0	24	56	105	138	156	168	178	182	186	193	198	214	1	28	41	96	117	133	153	168	189	204
Angulogerina bella								2			1	2								2			
Bigenerina irregularis											1								2				3
Bolivina alata										21										5	5	3	
B. albatrossi												2							4				
B. barbata											5	3								2		3	3
B. lowmani												8										5	
B. striatula spinata								5			3	2											
B. subaenariensis mexicana											3	5								5		11	
Bulimina aculeata												1							13	5		5	8
B. alazanensis											3	2							2				3
B. marginata								2			3	2									5		
B. striata mexicana								2			1	3										3	5
Cancris oblongo																			2	2			
Cassidulina subglobosa		1									1											5	
Cibicides aff. floridanus	3			3															4	5	2		5
C. wuellerstorfi	11	31	21	15	32	33			5			1	12	47	33	6	11	36			2	5	
Cibicidina strattoni											3	6							4	5	10	11	13
Eggerella bradyi	5		5	5	4	4							4			6	3	6					
Elphidium discoidale								5			31	24							18	25	20	8	30
E. cf. fimbriatulum												1							2				
E. gunteri											1	1							4	5		3	
Epistominella decorata	8	7	19	13	18	7			5		1		4		22	35	21	12	2				
Eponides polius	14	17	5											21									
E. tumidulus	3		9	5	8										11	12	14						
Globobulimina affinis						7	20	10	17	36								15	4	2	2	3	3
Glomospira charoides	25	1												5	11	6	3						
Gyroidinoides altiformis					4											12	3				2	3	
Nonion pompilioides	5	20	19	13	14	11	20						4	5	11		7	6					3
Nonionella atlantica												3							2	2	2		
Osangularia cultur		1	2								1												
Pseudoeponides umbonatus			5	10	4	7										6	3	9	2		2	3	
Rectobolivina advena											3	4									2		
Reussella atlantica								7		7	1								4	2			5
"Rotalia" beccarii parkinsoniana											8	9							4	7	7	3	3
"R." beccarii tepida																			2		2		
"R." translucens								2												2			3
Uvigerina parvula										21		2											
U. peregrina								10	5		5	6							11		2	12	11	5
Virgulina pontoni								5	11			2								2	2		



water Foraminifera some of which must have come from the continental shelf. The sediment containing these faunas probably has been displaced a distance of at least 300 miles.

Ericson *et al.* (1951, 1952) have published preliminary reports on numerous long, deep-sea cores from the North Atlantic. They have generalized on the faunas which occur in sands in these cores as follows (*op. cit.*, 1951, p. 963) : " Foraminifera, though never abundant, are usually present in the coarser sands. . . . There are almost without exception a few species which are characteristic on the continental shelf and slope sediments, such as *Elphidium incertum*, *Globobulimina auriculata*, and *Nonion labradoricum*."

Studies of submarine cores from the continental shelf of the northeastern United States were published by Phleger (1939, 1942). There are several faunas in these cores which contained displaced benthonic Foraminifera, and the displacement was not realized at the time those studies were published. Hamilton (1953, p. 216) has recognized displaced faunas near a flat-topped seamount in the central Pacific basin. Displaced faunas have been described from the San Diego Trough, off Southern California (Phleger, 1951a).

The possible significance of displacement in sedimentation in the deep sea has been summarized by Phleger *et al.* (1953, p. 120) based on their studies of cores from the North Atlantic :

" The widespread occurrence of displaced faunas may be of considerable importance to the deposition of sediment in the North Atlantic. The displaced faunas appear to be located near areas of considerable relief. Data from these cores and from elsewhere suggest that displaced faunas cover only a small percentage of an ocean basin, even though they may have considerable areal extent. It appears reasonable to assume that sediment being displaced to the deep ocean will carry an assortment of sediment from clay through sand sizes. It is expected that there will be differential sorting of these sizes as the sediment is moved downslope and gradually loses velocity, with the sand sizes deposited first, nearest the source. Tests of Foraminifera may be considered as sand particles in their reaction to processes of sediment transportation and deposition so that any Foraminifera which are contained in the sediment will be deposited along with the sand-size material. It is expected that they will be deposited along with grains of sand smaller than the tests themselves since they have a relatively low density per unit volume. The fine silt and clay sizes of the material being displaced will be carried beyond the coarser material and deposited. This fine-grained sediment is expected to carry no tests of Foraminifera since they have been deposited with the sand.

" It appears probable that some of the fine-grained sediment in the deep North Atlantic, far from sources of supply, is the fine fraction of displaced sediment. A considerable percentage of sediment in these deep basins thus may of be terrigenous origin. Deposition of the fine sediment by this mechanism should have no effect on the stratigraphic sequence of planktonic Foraminifera in these sediments. Interpretations of chronology based upon planktonic populations in cores collected from such areas are expected to be as valid as those from any area of the ocean."

Marine Foraminifera Laboratory,
Scripps Institution of Oceanography, La Jolla, California.

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Some effects of high hydrostatic pressure on apparatus observed on the Danish Galathea Deep-Sea Expedition

CLAUDE E. ZOBELL

Summary—Certain glass apparatus was adversely affected by hydrostatic pressure when submerged to great depths on the Danish *Galathea* Deep-Sea Expedition. Hollow glass balls, used to signal when collecting gear touched bottom, as well as reversing thermometers were broken by the pressure at depths exceeding 9,000 metres. Their failure, an implosion, was followed by a forceful explosion. An attempt is made to explain the explosion upon a basis of field observations. Capillary tubes used on the ZoBell bacteriological water sampler withstood pressures exceeding 1,000 atmospheres, but unless filled with water they were plugged and broken by the intrusion of connecting rubber pressure tubing.

INTRODUCTION

THE Danish *Galathea* Deep-Sea Expedition of 1950-52 afforded opportunities to observe some effects of high hydrostatic pressure on certain apparatus submerged to depths exceeding 9,000 metres. Reversing thermometers, thick-walled glass balls, and bacteriological water samplers (ZoBell, 1941) were found to be adversely affected by pressure of water in the Phillippine Trench, where at 10°13′N × 126°48′E the echo sounder on the *Galathea* recorded depths to 10,340 ± 100 metres (Bruun, 1951).

In this same vicinity the *Snellius* Expedition had previously recorded a depth of 10,130 ± 100 metres at 9°42·4′N × 126°51·2′E (Wüst, 1951), the *Emden* recorded a depth of 10,400 ± 140 metres at 9°42·1′N × 126°52·1′E (Mauer, 1937) and the U.S.S. *Cape Johnson* recorded 10,497 ± 91 metres at 10°27′N × 126°39·5′E (Hess and Buell, 1950).

GLASS BALLS

Submerged to depths exceeding 9,000 metres were several dozen hollow glass balls of the type used on the deep-water bottom signalling device described by Isaacs and Maxwell (1952). The device (Fig. 1) consists of a mechanism for breaking a hollow glass ball upon contacting the sea floor. The resulting sound is detected by a hydrophone, thereby indicating that the gear, to which the ball-breaker is attached, has touched bottom.

The glass balls were carefully selected for uniform size and apparent freedom from flaws. They were approximately spherical in shape, having an average diameter of 70 mm and a wall thickness of 2 to 3 mm, except at the site of sealing off where the thickness ranged from 5 to 10 mm. Preparatory to employing the ball-breaker on the corer, dredge, sledge-trawl, grab or other deep-sea gear, the glass balls were submerged in the sea to test them for their pressure tolerance. Although none of the balls were adversely affected by pressures prevailing at 6,000 metres (approximately 600 atmospheres), several failed when submerged to depths exceeding 9,000 metres (Table 1).

The hydrostatic pressure of sea water increases with depth by approximately 0·1 atmosphere per metre, the pressure-depth gradient being influenced to a maximum of about 5 per cent by latitude, temperature, and salinity. One atmosphere is equivalent to 14·696 psi, 760 mm Hg, 1·0332 kg/cm^2, or to 1·0133 bars.

It is noteworthy that 28 per cent of the 18 glass balls submerged to 9,200 to 9,300 metres were broken, whereas 62 per cent of the 26 submerged to 10,000 to 10,300 metres were broken. From 0·5 to 5 ml of water leaked into a few of the balls, as shown in the column headed " Took water " in Table 1. The absence of any obvious defects in the balls suggested that water might have been forced through the glass under the influence of pressure, but more careful inspection revealed that under the stress of pressure a capillary opening developed through the sealing-off point.

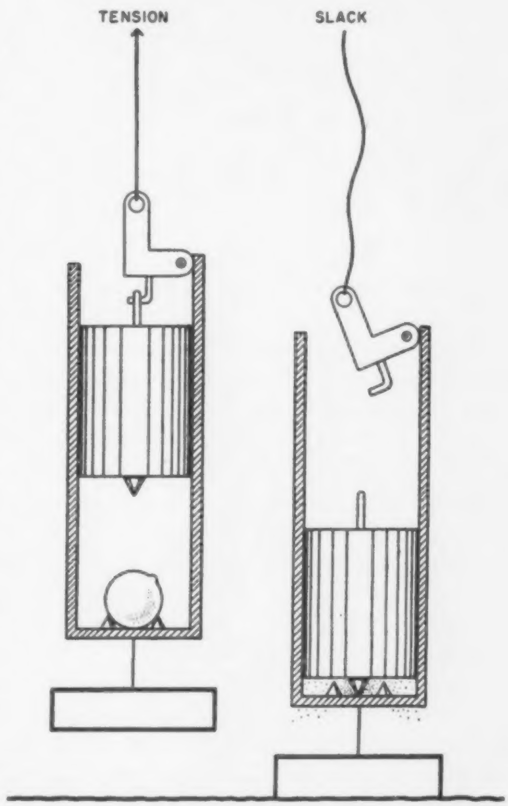


Fig. 1. Ball-breaker bottom-signalling device before (left) and after (right) hollow glass ball is broken by falling weight released by contact with the floor of the ocean.

In all the balls submerged to 9,000 or more metres, there appeared small quantities of minute glass particles that chipped off the interior surfaces during compression or subsequent decompression. Extremely thin sections of glass up to several square centimetres in area peeled off the outside of some of the otherwise intact balls, like layers of onion skin. Such sections were found in the containers in which the balls were submerged. This peeling off may have occurred during submergence owing to unequal stresses set up in different layers of glass or it may have resulted from the force of water squeezed into the outer layers of glass.

Poulter and Wilson (1932) attributed the shattering of solid glass rods compressed to 15,000 atmospheres to the penetration of glass by water which fails to escape and subsequently expands when the pressure is released. Purportedly at such pressures water penetrates solid glass to a depth of several millimetres within 15 minutes. No breakage of glass occurred when glycerol or mineral oil was employed instead of water as the hydrostatic fluid, presumably because the larger molecules do not penetrate glass. Similarly Bridgman (1952) observed the " pinching off " of glass with the release of pressure, water invariably causing breakage at much lower pressures

than such liquids as oils, alcohols, or glycerol. He concluded, however, that only extremely minute quantities of water penetrate glass at pressures up to 12,000 atmospheres. According to a private communication from Dr. J. W. WEST, extensive tests conducted by the Bell Telephone Laboratories for a period of several years failed to show any penetration of water through either Pyrex or type 7052 glass at pressures up to 600 atmospheres.

Table 1. *Condition of glass balls submerged in sea to stated depth*

Station number	*Station Location*		*Depth of submergence*	*Number submerged*	*Number broken*	*Took water*	*Number intact*
	Latitude	*Longitude*					
412	11°13′N	126°21′E	9,200 m	12	3	5	4
413	10°20′N	126°31′E	10,300 m	12	7	2	3
420	10°20′N	123°40′E	10,300 m	12	7	0	5
430	10°20′N	126°37′E	9,300 m	6	2	2	2
431	10°20′N	126°38′E	10,000 m	6	4	1	1
435	10°20′N	126°47′E	10,100 m	12	8	1	3

The fragmentation of the glass balls is similar in many respects to the collapse of Prince Rupert drops. These are made by heating a glass rod until it becomes syrupy. The resulting molten mass is dropped into cold water. Some of the molten glass drops fail to break, but are under high internal stress, the outside having solidified while the interior was still hot. As the interior cools and shrinks, high stresses are produced. The outer layers are under compressional stress that is approximately hydrostatic except at the very surface. When the surface of such a drop is broken, the whole mass collapses into very small fragments, most of the mass adhering together much like the remains of glass balls which collapsed under the influence of high hydrostatic pressure in the deep sea. In the case of Prince Rupert drops, the collapse is confined to the glass because the stresses are symmetrically disposed. In the hollow glass balls, bending stresses would cause a non-uniform collapse. After the initial break, at the point of highest tensile stress, there would be a general relief of the tremendous tensile stress present as a balance to the high compressive stress. This uncoiling of the tensile stress may result in the pulverizing of the glass and it may result in some explosive effect.

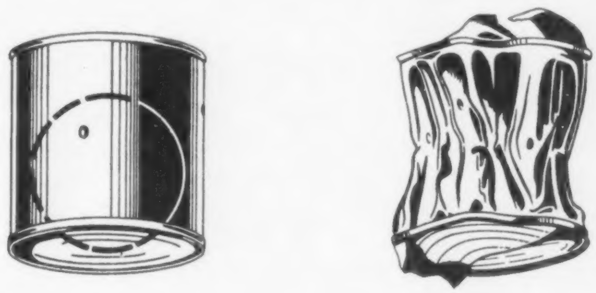
EXPLOSION RESULTING FROM BREAKING BALLS

There was evidence of an underwater explosion resulting from the breakage of hollow glass balls at high pressure. The balls were submerged in the sea by securing them in various kinds of receptacles lashed a few metres apart on the dredging cable. When encased separately in light-weight cloth sacks, ball breakage was indicated by the entire sack, except the fragment lashed to the cable, being torn off as if by a forceful explosion. This was confirmed by what happened when balls broke under water in sturdier receptacles.

Several balls were submerged separately encased in heavy-weight canvas sailcloth fashioned into sacks 25 cm wide and 30 cm long. Except for a pocket at the bottom designed to catch broken glass, the sack seams were loosely stitched in order to provide openings for the easy ingress and egress of water. Such sacks had jagged

holes up to 6 cm long torn in their sides by balls that broke at water depths of 9,000 metres or more. Some of the stout sailcloth sacks had their bottoms torn off. Judging from the tensile strength of the sailcloth, a force of several hundred pounds would have been required to tear the sacks asunder. The tattered remnants clearly showed that the tearing force had been outward—an explosion. In a few of the tattered sacks small quantities of pulverized glass occurred in the bottom corners.

In an effort to recover more of the spoil resulting from broken balls and to learn more about the phenomena, a series of balls were submerged within tin cans, size 10 cm in diameter by 10·5 cm tall. The sides and lids of the cans were perforated with numerous holes, about 4 mm in diameter, in order to permit the free passage



a b

Fig. 2. (a) Perforated can with enclosed glass ball prior to submergence in the deep sea. (b) Appearance of can after breakage of glass ball by pressure at depth of 9,000 metres.

of water. Those cans in which glass balls collapsed at great depths were buckled and bent, whereas those carrying unbroken balls back to the surface were not perceptibly altered (Fig. 2). The former were irregularly accordion-pleated to give an hour-glass shape, and both ends were concaved. These changes must have resulted from the inrush of water when the balls collapsed. The walls and ends of such cans were deformed further by jagged holes, irregular in shape and space with their edges bent outward. This out-breaking of holes must have been caused by a forceful explosion, after the walls and ends of the cans had been bent inward. Remains of broken balls consisted of pulverised glass occurring in amorphous agglomerates of various sizes.

Virtually all of the spoil from several broken glass balls was recovered in thick-walled (3 mm) copper cans 8 cm in diameter by 8 cm high. Such cans were fabricated on the *Galathea* by Bent Sorensen and A. Thegler-Jensen. The bottoms were brazed on and the tops were held in place by machine screws in such a position that there was an opening for the free passage of water. As in the more flimsy tin cans, balls breaking at great depths resulted in a collapse of the copper cans, accordion-pleated around the middle to give an hour-glass shape. Actually the inside diameter at the midsection of such cans was reduced from an initial 75 mm to 40 or 50 mm. The ends of the copper cans were also collapsed, the concavities having maximum depths ranging from 12 to 20 mm.

The interior walls were peppered with powdered glass, but no holes were torn

through these stout copper cans by the explosion that followed the collapse of the glass balls. About three-fourths of the glass spoil remained in the copper cans as an almost impalpable powder or in loosely agglomerated lumps up to 15 mm thick. The latter could be picked to pieces or crushed with one's fingers. Microscopic examination of the spoil showed that it consisted of amorphous fragments ranging in size from less than one micron to many microns. The edges of most fragments were sharp, although some seemed to be slightly blunted, frittered, or fused.

Cloth adhesive tape, originally wrapped around the glass balls to secure them in the desired position in the cans, was found to be practically pulverized by balls, breaking. This provides further evidence for an explosion of the glass, because in a simple implosion the tape would have been peeled off and left behind more or less intact. Instead, it was so finely shredded that the fragments were difficult to identify, intermixed with pulverized glass.

EXPLANATION OF EXPLOSION

These observations tell something about what happens when hollow glass balls are broken by high hydrostatic pressure. Apparently the balls are compressed to a point of failure, this probably being primarily a function of diameter, wall thickness, kind of glass, and particularly lack of homogeneity which cause shear stresses in the structure. When the ball breaks, water rushes into the air space so forcefully that rigid containers like cans are collapsed. The explosion that follows in the wake of the implosion is not so simple to explain.

Part of this explosive force may be attributed to a reflected shock wave, the reverse of that which occurs when dynamite is discharged under water (COLE, 1948). Water rushing towards the centre of the recently broken glass ball may bounce back with appreciable force carrying with it some of the fragments of broken glass, but this force would probably be damped out before its influence extended much beyond the locus of the broken ball.

According to a private communication from Sir EDWARD BULLARD of the British National Physical Laboratory, the expression for the time T between successive oscillations of the bubble pulse following an underwater explosion is

$$T = 1{\cdot}14\rho^{1/2}\, W^{1/3}\, P^{-5/6}$$

where ρ is water density, W is initial energy of gaseous products of explosion, and P is the total hydrostatic pressure. P is $\rho\, gH$ where H is the water depth and W may be roughly equivalent to PV, which gives

$$\text{frequency} = 6{\cdot}54\,\frac{\sqrt{gH}}{r}$$

where r is the radius of the sphere.

According to OSBORNE (1947), shocks produced by a collapsing cavity in water are recurrent and multiple, the time interval separating them depending primarily upon the size of the cavity. Abruptness or violence of the shock is dependent upon the size of the residual air bubble around which the cavity collapses. A Pyrex glass bottle, with walls 3 to 5 mm thick, was broken with collapse of air bubbles only 1 mm or less in diameter.

BAKER (1940) described the breaking of glass jars partly filled with water by

accelerating them so violently that a cavity was formed by the sudden departure of water. The bursting of the cavity caused the collapse of the glass jars.

Dr. Carl Eckart points out that the major energy from breaking balls must be liberated by the sudden collapse of the cavity, which contains some air. This collapse, however, is relatively slow because the cans are bent, not torn. Still considerable energy is liberated, and the inertia of the water that is set in motion will cause the pressure in the bubble, at the moment of smallest diameter, to be much higher than the ambient pressure. When a ball breaks at a depth of 10,000 metres, for example, the pressure to which the air bubble in the cavity is subjected will probably be considerably in excess of 1,000 atmospheres. The maximum ambient pressure is infinite when a spherical cavity is collapsed. This effect is similar to the " water hammer " action occurring when a water faucet is closed suddenly, resulting in the kinetic energy of moving water in the pipe being converted into pressure. This inrush of water at the moment of collapse could be expected to carry the fragments of broken glass into a very small volume and grind them together forcibly with the generation of considerable heat.

It has been calculated by Dr. T. R. Folsom that the maximum average temperature rise resulting from work done when a glass ball collapsed at 10,000 metres is about 480°C. The temperature in highly localized areas may be much higher. Cold water cooling the heated glass would result in thermal shock leading to fracturing.

Another explosive effect may result from the momentum or inertia of inrushing glass fragments carrying the latter through and beyond the locus of the ball (Fig. 3). The tendency would be for many of the glass fragments to collide as they approach the centre. Such fragments impinging upon each other and adhering in a state of semi-fusion may account for the amorphous lumps of loosely agglomerated glass fragments found as spoil. Since the glass balls are not homogeneous, there will be no smooth uniform progress of particles to the centre. Some particles will traverse the original outline of the sphere; others will bounce off the central or excentrically located mass. Owing to their random distribution, direction and difference in mass, not all of the flying fragments of glass would collide. Instead, many may continue to fly forward across the space formerly occupied by the ball and beyond with sufficient force to affect encasing containers.

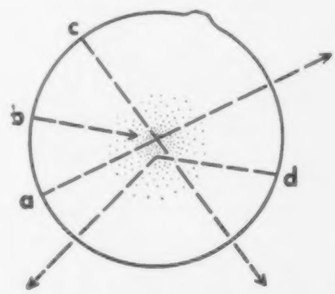


Fig. 3. Diagram illustrating theoretical trajectories of glass fragments when a hollow glass ball implodes (trajectories towards centre of ball) and explodes (trajectories outside of original outline of ball) under the influence of hydrostatic pressure.

This may be the movement of many glass fragments originating primarily from the inside of the balls, but additional explosive force may be generated by the glass fragments from the outside of the ball flying outward in all directions like countless springs uncoiling the instant the ball breaks, resulting in a sudden pressure change from nearly 1,000 atmospheres down to about one atmosphere. The compressibility of glass has been demonstrated by Bridgman (1952), who found that this property

increases with decreasing temperature. The temperature of the water in which the balls broke was approximately 2·5°C.

Another factor involved might be the manner in which the glass ball breaks. Assuming that the glass breaks at point of highest stress concentration before the glass envelope has been completely pulverized, the sea water would rush in primarily from one direction to fill the void. The inertia of the sea water in this direction with the glass particles, which by then would have been pulverized, would carry through toward the outer container with considerable kinetic energy. As a matter of fact, explosive force was randomly directional as indicated by highly irregular distribution and size of holes blown through the tin cans used as containers.

When two or more glass balls in close proximity were submerged to a depth of 9,000 or more metres, all or none of the balls in a common container were broken, although only about half of similar balls submerged a few metres apart to the same depths were broken. Presumably, the disturbance created when the weakest ball broke resulted in the collapse of adjacent balls.

OBSERVATION ON THERMOMETERS

Several protected reversing thermometers submerged to depths exceeding 8,000 metres were broken by the pressure. As with the glass balls that broke at such depths, there was evidence that an explosion followed the implosion. An inward bending of the metal housing surrounding the thermometer indicated a forceful implosion. An outward bending in local areas, or in some cases breakage of the metal housing, as well as the appearance of glass fragments in the surrounding metal parts, indicated an explosion. The spoil from the broken thermometers consisted of finely pulverized glass.

Not only was the protecting glass jacket (diameter 16 to 18 mm) broken but the two small-bore thermometers tubes within (one reversing and one auxiliary) were also broken. The failure of the latter must have resulted from the disturbance created by the breaking of the glass jacket or possibly the larger mercury-filled bulb, because such small-bore glass tubes can tolerate the greatest hydrostatic pressures occurring in the sea.

The spoil from one protected thermometer submerged to 9,000 metres was recovered almost intact. It appeared as a column of pulverized loosely fused glass. There were no discernible boundaries between the spoil from what had been the outer jacket and the inner thermometer tubes.

It was impractical for economic as well as for logistic reasons to submerge enough thermometers to get information of statistical significance on the exact depths of failure of various instruments. It may be noteworthy, however, that all of the six American-made (*Kahl Scientific Instrument Corp.*) thermometers submerged to 9,000 or more metres failed. Likewise two of the German-made (*Richter and Wiese*) thermometers were broken by pressures at depths exceeding 9,000 metres. The one and only Japanese-made (*Watanabe Keiki Mfg. Co.*) thermometer submerged to 9,000 metres was broken by pressure. A few temperature readings were made with English-made (*Negretti Zambra*) thermometers at depths exceeding 10,000 metres. The latter are smaller in diameter than other kinds of reversing thermometers. Their smaller diameter may account for their pressure tolerance, although it may have been purely happenstance that the few selected for the deep-sea stations

were better annealed. Those that failed might have had slight variations in thickness at the sealing-off point, resulting in high tensile and shear stresses in the glass, predisposing to failure when the thermometers were subjected to high pressures.

BACTERIOLOGICAL WATER SAMPLERS

Water samples for bacteriological analyses were collected from depths exceeding 10,000 metres by means of apparatus described by ZoBell (1941). Essentially the bacteriological water sampler consists of a pear-shaped collapsible rubber bulb, having a capacity of about 300 ml, fitted with a hermetically sealed capillary glass tube by means of a short length (15 cm) of flexible rubber tubing. When lowered to the desired depth, attached to the hydrographic wire by means of a brass holder, a messenger was dropped to activate a mechanism which broke the glass tube thereby permitting the rubber bulb to fill with water.

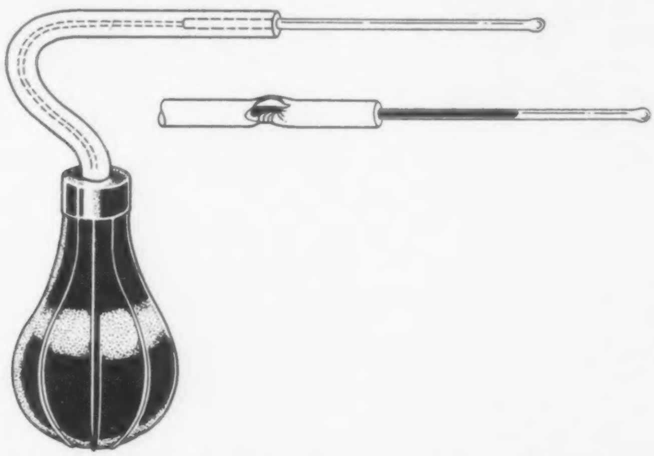


Fig. 4. Collapsible rubber bulb, pressure tubing, and hermetically sealed glass tube assembled for collecting water sample aseptically from any desired depth for bacteriological analysis. Inset shows failure at great oceanic depth due to water pressure's pushing rubber tubing into the open end of glass tube until wall of rubber tubing was punctured.

Although the capillary glass tube, having a bore of 2 mm and an outside diameter of 4 mm, withstood the highest pressures encountered on the *Galathea* Expedition, there were four failures caused by the rubber tubing's (1 mm bore and 4 mm wall thickness) being forced by water pressure into the open end of the glass tube (Fig. 4). Upon being collapsed over the open end of the glass tube, pressure pushed the thick-walled rubber tubing into glass tube until the rubber tubing was ruptured, thereby permitting the bulb to fill with water at the depth where the failure occurred. No such failures occurred at water depths of less than 8,000 metres. This defect was corrected by having the capillary tube filled with a few drops of sterile water prior to submerging the bacteriological sampler.

Some of the 300-ml rubber bulbs submerged to depths exceeding 9,000 metres reversibly lost some of their elasticity or resiliency ; they returned only slowly to their normal pear-shape after being collapsed. Consequently, one could not know at what depth such bulbs so affected by pressure filled with water. Ordinarily the

rubber bulbs are filled to capacity with water within a few seconds after being opened under water by breaking the capillary tube. As a rule they are hauled to the surface with water being ejected owing to the decrease in external pressure.

Further investigations are required to determine the extent to which various kinds of rubber or other elastomers are affected by deep-sea pressures. There seems to be a difference in the pressure tolerance of different rubber receptacles. According to THIESSEN and KIRSCH (1938), caoutchouc commences to crystallize at pressures ranging from 10 to 25 atmospheres at 7° to 10°C.

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The direct measurement of subsurface currents in the oceans

K. F. BOWDEN

Summary—Direct measurements have provided a comparatively small proportion of our knowledge of subsurface currents in the oceans. Such measurements are necessary, however, in order to confirm and supplement the estimates of currents obtained by other methods, and in this article a survey is given of the measurements which have already been made, mostly by current meter from an anchored ship. The apparatus and techniques employed in making the observations and the methods of analysing the data, in order to separate the mean current from the tidal and other periodic currents, are described briefly. The results of the measurements are discussed, particularly for the mean currents and semi-diurnal tidal currents in the Atlantic Ocean, where the greater part of the observations have been made.

1. INTRODUCTION: SOURCES OF KNOWLEDGE OF OCEAN CURRENTS

THE surface currents of the oceans have been determined mainly by the method of ship's drift, in which the drift due to the current is found as the vector difference between the distance travelled through the water, as measured by ship's log and course steered, and the distance travelled relative to the earth, as found by astronomical fixes at intervals of, usually, 24 hours. For most parts of the oceans, many thousands of such observations have been collected, compared and averaged, so that charts may be constructed showing the average or seasonal currents.

Knowledge of currents below the surface, on the other hand, has been obtained mainly by indirect methods. In addition to their interest from the point of view of the circulation in the ocean layers at various depths and its dependence and possible effects on climatological conditions, subsurface currents are of some importance in marine geology because of their influence on the transportation and deposition of sediment. Besides the effects of steady currents, the action of periodic currents, due to tides for example, in keeping material in suspension, and the greater turbulence and mixing which they may cause, are factors of interest. A knowledge of deep currents is also of biological interest because of their influence on the dispersal of organisms and the maintenance of supplies of nutrients. Cases of particular interest arise, for example, where regions of convergence or divergence in the horizontal movements are associated with vertical movements in the form of sinking or upwelling.

The greater part of the existing data on subsurface currents has been derived from dynamical computations, based on the distribution of density, as found from observations of temperature and salinity. In applying this method, it is assumed that the only forces acting on the water are gravity, the pressure gradients associated with the variations of density and the apparent geostrophic force due to the earth's rotation. It is assumed further that the accelerations are negligible, i.e. that the currents are steady in time and that their magnitude and direction change only very gradually with distance. On these assumptions it is possible to compute the current at one level relative to that at another level, provided the requisite observations of temperature and salinity are available. It is possible to deduce the absolute value

of the current at each level only if the current at one level is known by some other means, or may reasonably be assumed to be zero.

Frequently it has been assumed that the movements in the deeper layers are very slow and that a reference level taken sufficiently deep, say 3,000 m, may be regarded as at rest. Another procedure has been adopted by Defant (1941), in an attempt to deduce the absolute currents at all depths in the Atlantic Ocean. The surface of no motion is taken as lying within a range of depth in which the difference between the dynamic depths of corresponding isobaric surfaces at two neighbouring stations remains nearly constant. According to the method of dynamical computations, the current within such a layer, which is nearly always present, must either be zero within the layer and of opposite sign above and below it, or else constant within the layer, increasing above and decreasing below. Defant gives reasons for considering the former alternative to be more likely. A third method, which is very effective where sufficient data exist, is to apply considerations of continuity. For example the flow of water at various levels across a parallel of latitude in the South Atlantic Ocean must be such that, on the average, the net flow from surface to bottom is zero, since no appreciable amount of water can be accumulated or removed from the North Atlantic, which is practically closed at the northern end. The relative currents having been computed, this consideration enables the depth of the layer of zero current to be fixed.

It is almost certain that the currents are much smaller in the deeper layers than nearer the surface, so that the currents in the upper layers may often be found to a sufficient approximation by neglecting the movements at great depths. On the other hand, the movements of the deep and bottom layers, although slow, are far-reaching in their effects, and play an important part in the general circulation of the oceans, so that it is of interest to know what these movements are. For example, it is believed that the deep and bottom water of all the oceans is derived largely from the Antarctic and Subarctic regions of the Atlantic. The Antarctic bottom water has been traced as far as 35°N while the North Atlantic deep water reaches the slopes of the Antarctic continent.

The movements in the deep and bottom layers have been deduced mainly from the distribution of temperature and salinity or oxygen content. It is assumed that the temperature and salinity of a water mass are relatively conservative properties, which are changed only slowly by eddy diffusion and mixing with adjacent water masses. The oxygen content of a deep water mass, besides being affected by such processes, must also tend to decrease owing to its consumption by biological processes. These methods are more suited to qualitative deductions as to the directions of motion, than to quantitative estimates of their velocities, since similar distributions of temperature and salinity may be brought about by different combinations of mixing effects and water movements. The distribution of other properties such as phosphate, nitrate or silicate content have been used as indicators of deep water movements, but more caution is needed in their interpretation as they are affected also by biological processes.

It is very unlikely that an amount of data on deep currents, in any way comparable with the mass of material on surface currents, will ever be accumulated by direct measurements. Nevertheless, owing to the uncertain assumptions on which the indirect methods of determining deep currents are based, and the necessarily broad

picture which they usually give, it is important that direct measurements should be made in some positions, to check their validity and possibly to give more detailed information in particular areas. Direct measurements are also a means of obtaining useful data on tidal currents, currents associated with internal waves and currents due to turbulence, which cannot be investigated satisfactorily by other methods.

The purpose of this article is to give a survey of the direct measurements which have already been carried out, describing briefly the equipment and technique used in the measurements, the methods of analysis, the results obtained and their comparison with the deductions by indirect methods.

2. EXPEDITIONS ON WHICH DIRECT CURRENT MEASUREMENTS HAVE BEEN MADE

Table 1 gives a list of the expeditions on which direct measurements of currents below the surface have been made successfully, with some details of the ship, the number of anchor stations and their duration, the depth of water, the type of current meter used and the depth to which current measurements were made. It does not include measurements in shallow water, which are much more numerous.

The work by Pillsbury from the *Blake* in the Gulf Stream in 1888-89 was a remarkable pioneer achievement in that it was the first time systematic current measurements had been made from an anchored ship in deep water. The ship was anchored by a single anchor in depths to 1,000 m, and in one case 4,000 m, in currents up to 5 kts. The current meter, of Pillsbury's own design, measured the speed of flow by four cups rotating *in* the plane of the current (unlike subsequent instruments). The cups rotated continuously while the meter was in the water and a correction was applied for the number of revolutions turned while the meter was being lowered to and raised from its position. It had a magnetic compass which was clamped on starting to haul the meter up, so that there was only one reading of direction for each current measurement. Besides the measurements in four sections across the Florida current and one across the Gulf Stream off Cape Hatteras, Pillsbury made measurements in a section across the Yucatan Channel and at a number of stations in the passages between the islands of the Antilles arc. The strong currents in which Pillsbury worked no doubt made anchoring more difficult, but on the other hand they probably reduced the movements of the ship while at anchor and reduced the proportional errors due to this cause in the current measurements.

The greatest problem in measuring currents in deep water arises from the impossibility of providing a fixed point of suspension for the current meter. Even when the length of anchor cable in excess of the depth of water is reduced as much as is practicable, the ship can still execute appreciable movements of three kinds, which have been called " over-riding " – the movement of the ship radially to and from a point vertically above the anchor, " swing " – the rotation of the ship in an arc with the point above the anchor as centre, and " yaw " the rotation of the ship itself about its bow. The swinging and yawing can be observed by keeping a record of the ship's bearing and the lead of the anchor cable away from the bow, but over-riding cannot be observed, except in the presence of a fixed mark, such as a buoy moored by a taut wire or, over a period, by astronomical fixes.

All the measurements at anchor stations, from Pillsbury's onwards, have been made with the ship anchored by one anchor. The use of two or three anchors, in

Table 1. Deep-sea expeditions on which subsurface currents have been measured.

Ship	*Date*	*Area*	*Reference*	*Ship's length and tonnage*	*No. of stations*	*Duration of stations*	*Depth of water*	*Length of cable / Depth of water*	*Type of current meter*	*Depths of current measurements*
Blake	1888-89	Gulf Stream, West Indian waters	PILLSBURY (1891) WÜST (1924) v. SCHUBERT (1932)	147 ft. 218 tons	39	Up to 166 hr.	Mostly to 1,000 m once 4,000 m	1·5 to 2 some-times 3	Pillsbury	6 to 238 m (a few deeper)
Michael Sars	1910	(*a*) Straits of Gibraltar	HELLAND-HANSEN (1930)	125 ft. 226 tons	1	15 hr.	400 m	1·5	Ekman	To 250 m
		(*b*) S. of Azores			1	14 hr.	1,000 m		Ekman	To 730 m
Meteor	1925-27	Atlantic be-tween 24°N & 28°S.	DEFANT (1932)	220 ft. 1,180 tons	9 (+ 3 test stations)	29 to 51 hr.	2,150 to 5,365 m	About 1⅓	(i) Ekman-Merz (ii) Ekman repeating	Various depths to 2,500 m (few be-low 1,000 m)
Willebrord Snellius	1929-30	Dutch East Indian waters	LEK (1938)	204 ft. 1,055 tons	7	24 to 89 hr.	1,150 to 4,850 m	1⅓ to 1½	(i) Ekman-Merz (ii) Ekman repeating	To 3,000 m (few below 1,000 m)
Armauer Hansen	1930	N.E. Atlantic	EKMAN & HEL-LAND-HANSEN (1931) EKMAN (1953)	76 ft. 59 tons	6	49 to 141 hr.	1,805 to 3,970 m	1·05 to 1·33	(i) Ekman (ii) Ekman re-peating (iii) Sverdrup - Dahl	5 to 1,000 m (a few at 1,400 and 2,000 m)
Meteor	(*a*) 1937 (*b*) 1938	N. Atlantic N. Atlantic	DEFANT (1937) BÖHNECKE (1937) v. SCHUBERT (1939)	as above	1 2	52 hr. 60 hr.	2,140 m 2,950 and 2,210 m	1·7 to 1·8	Böhnecke Böhnecke	8 depths to 800 m
Altair	1938	N. Atlantic	DEFANT (1940)	4,000 tons	1	90 hr.	1,100 to 1,330 m	About 4	Böhnecke	5 to 800 m

order to reduce further the movements of the ship, does not appear to have been attempted in deep water, and may be quite impracticable, although this method has been used in shallow water. A detailed account of the gear and methods which have been employed for anchoring in deep water has been given by SPIESS (1932). SEIWELL (1941) has given a description of the method of anchoring used in the *Atlantis*. A number of deep anchor stations have been occupied by this ship for the purpose of making repeated observations of temperature and salinity, but, with the exception of one anchoring in the Gulf Stream, no direct current measurements were made.

The smallest ratio of length of anchor cable to depth of water was achieved in the 59-ton *Armauer Hansen* on the 1930 expedition, when at several stations the length of wire was only 5 to 10 per cent in excess of the depth of water. The anchoring equipment consisted of galvanised steel rope of diameter tapering from 11 mm to 9 mm with 55 m of chain, weighing 310 kg, a " star " anchor of special design weighing 150 kg at the end, and four mushroom anchors, each of 50 kg, on pendants 4 m long, spaced at intervals of 6 m.

The determination of the ship's movements by frequent observations of the ship's head, the angle to the vertical and relative bearing of the anchor cable, checks of depth of water by echo-sounding, measurements of surface current by log, allowance for wind and state of sea, and checks by astronomical fixes whenever possible, was given careful consideration at the *Meteor* anchor stations. It has also been the subject of careful analysis for the *Armauer Hansen*. and other subsequent anchor stations. When all precautions are taken, it seems possible to eliminate the ship's movements from the subsurface current measurements and to obtain corrected observations, which represent the true currents with considerably greater accuracy than one would, at first sight, suppose. Nevertheless, it seems likely that errors equivalent to a current of several cm/sec, which is probably of the order of magnitude of the deep currents themselves, may sometimes remain undetected in the current measurements.

The use of a reference buoy, moored by an almost taut wire, was tried by EKMAN and HELLAND-HANSEN (EKMAN 1953), but the wire broke away each time at the point of attachment to the buoy. Experiments from R.R.S. *Discovery II* and from H.M.S. *Challenger* on her recent voyage have shown, however, that it can be done by attaching the sinker and the buoy to piano wire with 60 feet or so of hemp rope.

The measuring instrument which has been most used, since PILLSBURY's observations, is the *Ekman* current meter, either in its original form as designed in 1905 (EKMAN 1905), or the improved *Ekman-Merz* form (MERZ, 1921). In this instrument the speed of the current is measured by recording the number of revolutions of a propeller in a given time, and its direction is obtained from the distribution of phosphor bronze balls which are released at intervals and are directed by a magnetic compass into a box divided into thirty-six compartments, each corresponding to an angle of 10°. For the greater depths the *Ekman* repeating current meter (EKMAN 1926) has proved an advantage. Unlike the ordinary *Ekman* meter, which has to be brought up after each measurement, the repeating current meter enables up to 47 measurements to be made before it is brought back to the surface. The *Sverdrup-Dahl* current meter (SVERDRUP and DAHL 1926) used for measurements at the lesser depths only, during the *Armauer Hansen* 1930 expedition, is suspended by an electric cable and the recorder is on board ship. In the *Böhnecke* current meter, used on the later

Meteor and the *Altair* expeditions, the speed and direction are recorded on a tin-foil strip in the instrument itself (Böhnecke 1937).

In addition to the measurements by current meter from an anchored ship certain other methods have been attempted from time to time. Helland-Hansen (1907), using a current meter from a small boat, moored by two anchors on lines which were almost taut, made measurements in Norwegian fjords and off the Norwegian coast, in depths up to 450 m. In 1913, using the same method, he recorded for 9 hours on the Rockall Bank, in a depth of 370 m. He tried the same method in the Straits of Gibraltar in 1910, but gave up the attempt, since he was more successful in anchoring the ship – the *Armauer Hansen* – instead. Single series of current measurements were carried out from a boat, moored by one anchor, from the *Deutschland* at two stations in the equatorial Atlantic in depths greater than 3,000 m, as reported by Brennecke (1911).

Current drags were used in deep water on the *Challenger* expedition (T. H. Tizard *et al.* 1885), at depths down to 500 m in an attempt to determine the movements at these levels relative to the surface. The drag was in the form of a cross, made up of two frames, 4 ft. square, covered with canvas, with a ½ cwt. weight hung below and suspended by cod-line from a buoy. Experiments have been carried out from *Discovery II* with current drags, constructed of canvas-covered frames 6 ft. square, suspended by up to 2,000 m of piano wire from a pair of pellets. Current drags have also been used by Stommel (1953) recently, near Bermuda. In using current drags, it is assumed that the buoy follows the movement of the drag, as affected by the deep current only, and that the effect of surface current on the buoy itself may be neglected. It is difficult to ensure that the effect of the surface current is negligibly small, since although the effective area of the drag is much greater, the deep current may be much slower.

3. THE INTERPRETATION OF CURRENT MEASUREMENTS

The measurements made by current meters usually consist of the average speed and direction over a period of the order of 10 minutes at intervals of one to two hours at each depth, for a total period of several days. One method of analysis is to start by plotting the observations of speed and direction against time, when any gross errors in the observations may be detected and rectified, and some degree of smoothing introduced in drawing curves through the observed points. From the curves, hourly values of speed and direction may be read off and converted into northerly and easterly components, which are then available for further analysis. Alternatively, the observed values themselves may be expressed as northerly and easterly components before plotting them and drawing the curves. If the main interest, as far as the periodic constituents are concerned, is in the lunar periods, the values may be read off at intervals of lunar, instead of solar, hours.

The next stage is to carry out harmonic analyses for the constituents of such periods as one expects to find in the observations, usually the lunar semi-diurnal and diurnal periods in any case. Other periods may suggest themselves from the course of the curves. The inertial period of half a pendulum day (see Section 4 (*e*)) is one period which may occur, and others of no obvious dynamical significance have been found in some sets of observations. It should be stressed that in order to be able to assert the significance of an oscillation of a particular period, and to derive

reliable values for its amplitude and phase, the observations should extend over a number of complete periods. This point has been discussed fully in a recent paper by HAURWITZ (1953). Having obtained the amplitude and phase of the northerly and easterly components of a constituent, it is convenient to combine them to give the ellipse traced out by the current vector during each period. The ellipse is defined by the amplitude of its major and minor axes, the direction of the major axis, the direction of rotation and the phase.

After harmonic analyses for the periodic constituents have been carried out, the current due to these constituents may be reconstructed for each hour and subtracted from the original values, leaving a residual current. This residual will consist of the mean current, probably with variations superimposed on it, which may be due to errors in measurement, ship's movements, transient currents due to wind, turbulent fluctuations or, possibly, a trend in the mean current itself. The possibilities are so numerous that it appears necessary to consider each set of measurements on its own merits. The type of data required to provide some check on the movements of the ship has been described above. Even when quantitative corrections cannot be made, it may be possible to decide that a given variation in current is consistent with the observed motion of the ship or, in another case, that it could not have been caused in this way. Variations of current near the surface may be found to be correlated with variations in wind. Variations due to turbulence are considered further below.

The mean current at each depth may be computed from the mean northerly and easterly components, derived from the residuals, as found above. If the mean current only is of interest, an approximate value may be obtained by averaging the original values of the components, but if a periodic constituent is prominent, such an average should, of course, be taken over an integral number of periods.

4. RESULTS OF CURRENT MEASUREMENTS

(a) *Mean current*

The results of direct current measurements in the Atlantic Ocean are illustrated in Fig. 1. Measurements at a depth of less than 100 m below the surface have not been included, since they are often affected by drift currents due directly to the wind blowing at that place at the time. Measurements at depths of 100 m and greater have been divided into three groups, corresponding to the upper layer (100 to 500 m approximately,) intermediate layer (500 to 1,500 m approximately), and deep layer (1,500 to 3,000 m approximately). The depth limits of the layers have not been applied rigorously, and in fact the actual transition between two water layers in the ocean occurs at different depths in different areas. Thus a measurement at 600 m has been included in the upper layer, rather than the intermediate, if it was similar to the measurements above but different from those below, and in the same way a measurement at 1,200 m was included in the deep layer if it resembled those at greater depths rather than those in the intermediate layer above.

Plotted in this way, the observations appear very few and widely scattered. It is interesting to compare the results with those found by other methods, e.g. the charts given in " The Oceans " (SVERDRUP, JOHNSON and FLEMING 1942) for the movements of the upper water masses (Fig. 187, p. 684) and of the intermediate water masses (Fig. 188, p. 685). One may also refer to the charts given by DEFANT (1941), in

which the currents at the surface, 800 m and 2,000 m are given, as derived from the absolute dynamic topography, and to the charts given by WÜST (1935) or DEFANT

Fig. 1. Measurements of mean current in the Atlantic Ocean.

A—Armauer Hansen stations
Alt—Altair stations
B—Blake stations
M—Meteor stations

——→ Upper layer (100 to 500 m approx.)
– – – → Intermediate layer (500 to 1,500 m approx.)
· · · · → Deep layer (1,500 to 3,000 m approx.)

(1938), in which the movements of the Antarctic intermediate water are indicated by the percentage of the Antarctic intermediate water in the " core " (at the depth of the salinity minimum), and those of the North Atlantic deep water by the oxygen

content in its " core " (at the depth of the oxygen maximum). WÜST (1933) and DEFANT (1938) have given charts in which the spreading of the Antarctic bottom water is shown by the lines of equal potential temperature but probably no current measurements have been extended deep enough to be in the bottom water.

In Fig. 1, PILLSBURY's measurements in the Florida Current are shown on a scale one-tenth that of the other measurements. The arrows represent the mean velocity from 6 to 238 m in the strongest part of the current. His measurements were analysed by WÜST (1924), who found a remarkable agreement between the distribution of velocity across a section in the narrowest part of the Florida Strait as given by PILLSBURY's measurements and as computed by the dynamical method from the distribution of temperature and salinity. WÜST also compared PILLSBURY's measurements at other sections with calculated values and found good agreement. PILLSBURY's own presentation of measurements was not in a very convenient form, and it appears that his data have never been completely utilised.

A comparison of the direct measurements with the currents deduced by other methods shows good agreement in some cases, but complete disagreement in others. Thus the general northerly movement in all layers at *Armauer Hansen* station *B* and the easterly movement in the upper layer at station *F* are in agreement with the dynamic topography (HELLAND-HANSEN and NANSEN, 1926). The westerly movement in the upper and intermediate layers at the *Altair* station was attributed to a counter-current on the northern edge of the Gulf Stream. At *Meteor* station 214 the current in the upper layer corresponds to the North Equatorial Current, but DEFANT (1941) indicates no appreciable current at 800 m. The eastward current in the upper layer at *Meteor* station 229 corresponds to the Guinea current, but the westerly current in the intermediate layer, interpreted as a compensation current, has not been indicated by any other method.

The measurements at *Meteor* station 288 are quite contrary to expectation, since the measured current in the intermediate layer is southerly, where the north-going Antarctic intermediate current would be expected, and the measured current at 3,000 m (although derived from two measurements only) is towards the north, where the south-going Atlantic deep water would be expected. A northwesterly and stronger deep current was measured at 2,000 m at station 254, and in this case DEFANT's chart for 2,000 m does indicate a deep counter-current towards the northwest not far to the east of this position.

At the other stations in the South Atlantic, the measured currents in the intermediate and deep layers are weak and the indirect methods also indicate weak or indefinite currents, so that no significant comparison is possible.

Even when determinations of deep currents, based on several days' observations, are not in agreement with the deductions by indirect methods, it does not necessarily follow that either is wrong. The study of conditions in the surface layers has shown that the broad picture of a general circulation often obscures details, such as eddies and counter-currents, which may vary in position and intensity, so that it is by no means uncommon for a current determination, at one position on a particular day, to differ considerably from the average current indicated for that area. It is not known to what extent similar variations in space and time may be a feature of the deeper water movements.

Outside the Atlantic Ocean, the current measurements on the *Snellius* expedition in Dutch East Indian waters should be mentioned. Most of the stations were in passages connecting ocean basins or seas, as the main object of the measurements was to study the exchange of water masses between the various basins. Large currents were recorded, up to 75 cm/sec in the upper layers but less in the deeper layers. The strongest deep current was 13 cm/sec at 1,000 m in Sawoe Strait, flowing south-westwards from the Sawoe Sea into the Indian Ocean. In the upper layer the current was in the opposite direction.

(b) *Tidal Currents*

Semi-diurnal tidal currents, in which the current vector describes an ellipse in the course of a period of 12 hr 25 min., have been recorded at very nearly all stations and all depths at which current measurements have been made. They are probably the most consistent feature of current measurements in the open ocean, although their amplitude, of the order of 10 cm/sec, is much less than in shallow waters.

Tidal currents were shown in Pillsbury's observations, referred to above, and an analysis of them at four of his stations was made by v. Schubert (1932). A detailed account of the observations of tidal currents in the Atlantic has been given by Defant (1932), taking into account the stations of the *Blake*, *Michael Sars* and *Armauer Hansen* as well as the *Meteor* stations.

According to theory, the tidal current should have the same amplitude and phase at all depths from the surface downwards, with the exception of frictional effects in a layer adjacent to the bottom. In an infinite ocean, the current vector should describe an ellipse in the *cum sole* direction, the ratio of the minor to the major axis being given by $(2\,\omega \sin \phi)/\sigma$, where ϕ is the latitude, ω is the angular velocity of the earth's rotation and σ the angular speed of the tidal constituent concerned. For the lunar semi-diurnal constituent the ratio is $1{\cdot}033 \sin \phi$.

The observed variation of tidal current with depth is not of the same type at all stations. At some stations the current has nearly the sample amplitude and phase at all depths. At others, changes of several hours in phase and two- or three-fold changes in amplitude may occur in a narrow range of depth. In such cases, steep gradients of temperature and salinity have been found at corresponding depths and repeated serial observations have shown a rise and fall of the isothermal and isohaline surfaces with the tidal period. It appears that these variations are due to internal waves, the vertical movements being necessarily associated with horizontal currents, which are superimposed on the normal tidal currents. It is characteristic of internal waves that there should be no net flow across a vertical section from surface to bottom, so that if the current is averaged with respect to depth, the currents due to internal waves should be eliminated and the ordinary tidal currents isolated.

By taking depth means, Defant found that the mean tidal current at the various anchor stations in the Atlantic Ocean varied systematically with position, showing the following features:

(1) The direction of the major axis of the current ellipse is approximately parallel to the axis of the Ocean, i.e. roughly south-east to north-west in the South Atlantic and south-west to north-east in the North Atlantic.

(2) The phase of the current becomes progressively later from south to north, the maximum northward flow occurring 3 hours after a lunar transit at Greenwich in 28°S, 8 hours near the equator and 3 hours on the eastern side in 30°N. On the western side in this latitude (as shown by three *Blake* stations) the current is almost exactly 6 hours out of phase with that on the east side in the same latitude. This is consistent with the existence of an amphidromic region in the North Atlantic, as indicated by the observations of tidal elevations on the coasts.

(3) The amplitude of the tidal current is least near the equator (about 6 cm/sec) and increases towards north and south, to about 10 cm/sec in 30°S and rather higher in 30° to 40°N.

(4) The ellipse is described *cum sole* (in agreement with theory) in 85 per cent of the cases.

(5) The ratio of the minor to the major axis of the ellipse increases with latitude and its magnitude agrees quite well with the theoretical ratio.

In the paper mentioned, DEFANT has tabulated the direction of the major axis, the amplitude, phase, ratio of axes and direction of rotation of the ellipse for each depth at each station and has illustrated the mean values by a chart. Table 2 gives

Table 2. Mean values of semi-diurnal tidal currents in Atlantic Ocean.

Anchor station		*Lat.*	*Long.*	*No. of values*	*Mean phase (Gr. lunar time)*	*Mean amplitude*	*Remarks*
					hr.	*cm/sec*	
Blake	5	35 °N	74 °W	5	6·1	13·2	
Blake	31	28 °N	77 °W	2	4·8	12·0	
Blake	5B	13 °N	60 °W	5	4·7	16·0	
Altair		44·5°N	39·0°W	7	0·8	8·3	
Michael Sars	58	37·6°N	29·4°W	1	11·4	24	at 9 m only
Meteor	438	30·0°N	43·8°W	8	3·8	5·4	
A. Hansen *Meteor*	D, E Vorexp.	29·5°N	15·5°W	9	2·0	10·4	
Meteor	385	16·8°N	46·3°W	8 (4)	8·8 (11·0)	8·2 (7·4)	Figures in brackets re-
Meteor	288	12·6°N	47·6°W	5	10·4	8·7	fer to measurements
Meteor	229	4·0°N	1·0°W	7 (4)	5·7 (5·0)	6·1 (5·8)	at 100 m and below,
Meteor	214	3·5°N	26·0°W	7 (4)	7·9 (6·8)	9·3 (10·4)	only.
Meteor	254	2·5°S	34·9°W	4	10·4	5·9	
Meteor	241	3·8°S	1·1°E	4	8·4	7·3	
Meteor	186	9·0°S	10·9°E	4	5·3	6·4	
Meteor	147	15·0°S	0·1°W	4	2·4	9·9	
Meteor	176	21·5°S	11·7°W	6	4·1	8·8	
Meteor	36	28·1°S	19·3°W	4	3·5	10·6	

the mean phase and amplitude for each station, taken from DEFANT, with the addition of the two *Meteor* stations Nos. 385 and 438 of the 1938 expedition and the *Altair* station. The phase is given as the time of maximum current northwards in lunar hours after a transit of the moon at Greenwich. The results for station 385 and the *Altair* station fit in well with the general distribution of amplitude and phase

deduced from the previous results, but the phase at station 438 is 3 to 4 hours later than would be expected. There were a number of breaks in the records below 100 m and it is possible that the results are less reliable than at the other stations.

Defant has compared the observed currents with those predicted by a theoretical treatment of the semi-diurnal tides of the Atlantic, applicable to conditions near the centre line of the Ocean, which he has given. The phase becoming progressively later from south to north is a feature in which observation and prediction agree. The observed amplitudes, of the order of 8 cm/sec, however, are two or three times as large as the predicted values, which were of the order of 3 cm/sec. The discrepancy may be due partly to the difficulty of deriving an adequate depth-mean of current when the observations include the effects of internal waves. Few series of measurements have been extended below 1,000 m and when, as at some *Meteor* stations, there were some measurements at 2,000 or 3,000 m, there was usually a gap from 700 m to this depth.

In the *Snellius* observations also, the semi-diurnal currents were prominent, with amplitudes up to 44 cm/sec. Since most of the stations were in passages or straits connecting basins, the results cannot be regarded as typical of the open ocean. Considerable variations of amplitude with depth occurred. The ratio of the minor to the major axis of the ellipse tended to be somewhat greater than the theoretical value, while the direction of rotation appeared rather random, as might be expected in an equatorial region.

Diurnal oscillations of current have been observed at many stations, but their occurrence appears to be considerably more variable and less systematic than the semi-diurnal currents. It is frequently uncertain how far the diurnal currents are to be attributed to the diurnal constituents of the tide-generating forces and how much to other causes. Because it has seldom been possible to obtain observations covering more than two or three complete periods for analysis, it has not been possible to derive the amplitudes and phases, or even to assign the exact period, with the same accuracy as for the semi-diurnal currents.

Large variations with depth have been found in the amplitude, phase, principal direction and ratio of minor to major axes of the diurnal current ellipses at a given station. Defant concluded that the observed values of phase of the diurnal currents at the *Meteor*, *Blake* and *Armauer Hansen* stations were in fair agreement with a theoretical treatment of the diurnal tides of the Atlantic, but the amplitudes were not considered.

Ekman (1953) found diurnal oscillations of considerable amplitude at three *Armauer Hansen* stations, of the order of 20 cm/sec, usually decreasing with depth. At two of the stations (D and E), the diurnal period coincides almost exactly with half a pendulum day. In the upper layers the current orbits were nearly circular and described *cum sole*, thus having the character expected of pure inertia oscillations, and Ekman interpreted them in this way.

Diurnal oscillations were also a feature of the current observations of the *Snellius* expedition (Lek 1938) with amplitudes up to 27 cm/sec, and again they were found to vary more with depth than the semi-diurnal currents. Lek suggested that the diurnal tidal currents were much influenced by the effects of wind and barometric pressure, which also vary with a diurnal period.

(c) *Internal waves*

Where the density varies with depth, internal waves may be set up, which are characterised by an amplitude which is small at the surface and zero at the bottom but reaches a maximum at some intermediate depth. The vertical oscillations are accompanied by horizontal currents whose amplitude and phase vary with depth. The theory of progressive internal waves in water in which the density varies continuously with depth has been given by FJELDSTAD (1933). For a given distribution of density and a given period, an infinite number of internal waves is possible, each with a different velocity of propagation and a different variation of amplitude with depth. The theory indicates that the greatest vertical amplitude should usually occur near the depth where the density gradient is steepest, while the current should be zero at the depth where the vertical amplitude is greatest and in opposite directions above and below. When the internal waves are superimposed on a tidal current, which is uniform with depth, these relations will be modified but considerable changes in the amplitude and phase of the current may be expected to occur near the depth of the steepest gradient of density.

An example of these conditions is provided by *Meteor* station 385, on the mid-Atlantic Ridge. The observations of temperature, salinity and current all showed semi-diurnal oscillations. The surface layer was practically uniform to 60 m, the steepest gradient in temperature and salinity occurring between 90 and 100 m. The vertical amplitude of oscillation was computed to be 12 m at 100 m. The phase of the current was nearly constant from 5 to 50 m, increased by about 4 hours at 100 m, and then remained nearly constant at greater depths. The amplitude of the current reached a minimum at 100 m but had maximum values of 11·6 cm/sec (phase 6·6 hours) at 50 m and 12·3 cm/sec (phase 10·6 hours) at 300 m.

Another example is given by station 253a of the *Snellius* expedition where internal waves of diurnal period were prominent in the temperature salinity and current observations. Using the observed distribution of density, FJELDSTAD's theory was applied, and the values of amplitude and phase were found which gave the best agreement with the observed vertical movements, as deduced from the temperature and salinity data. From these the currents were computed and were found to be in good agreement with the measurements.

The occurrence of internal waves is widespread wherever a density gradient exists, and has been established in most cases in which serial observations of temperature and salinity have been made as well as current measurements. Where the density gradients are small, however, internal waves are not prominent and the currents of tidal periods are more uniform with depth.

(d) *Wind drift*

In the surface layer a drift current due directly to the local wind may be present. The deviation of the surface current by about 45° to the right of the wind in the northern hemisphere and to the left in the southern hemisphere, in conformity with EKMAN's theory, has been fairly well confirmed by surface observations. The progressive increase in the deviation with depth and the exponential decrease in the magnitude of the current, the features of the "EKMAN spiral," have not been so well established by the current measurements below the surface. At several of the

Meteor stations, the observations down to 50 or 100 m were consistent with a drift current of the EKMAN type. For the last three days at the *Armauer Hansen* station *D* of 1930, the measurements in the upper layer were arranged to investigate the existence and character of the drift current. During that time the wind was blowing from an almost constant northerly direction, with a speed varying between 5·0 and 8·6 m/sec. After removing the diurnal and semi-diurnal oscillations, the measurements still showed considerable variations, but by plotting mean values over 54 hours, a diagram resembling the " EKMAN spiral " was obtained. The question of the response of the surface current to wind and the propagation of the movement downwards is an interesting one, which still needs further observations.

(e) *Inertia currents*

If a current is set up in any way in the open sea and is then left under the action of no forces except the apparent geostrophic force, then it should tend to continue to flow in such a way that the current vector describes a circle in the *cum sole* direction, with a period of half a pendulum day, given by $T = 12/\sin\phi$ hours, where ϕ is the latitude. The diurnal oscillations found at *Armauer Hansen* stations *D* and *E*, where the inertia period is almost exactly a solar day, and which were interpreted by EKMAN as inertia currents, have already been mentioned. Another example was given by the measurements at the *Altair* station, where a rotating current with a period of 17 hours, corresponding to the inertia period in that latitude, was found and persisted with almost undiminished amplitude during the 3½ days' observations. There was a complete reversal in the phase of the current between 15 and 30 m, the phase then changing gradually from 100 to 500 m, and more rapidly to 800 m, where the phase was opposite to that at 100 m. The amplitude of each component of the current was 7 cm/sec at 5 m, increasing to 12 cm/sec at 50 m and then decreasing to 5 cm/sec at 300-500 m. It may be noted that at the same station, the semi-diurnal tidal current (amplitude 8 cm/sec) varied little in amplitude or phase from the surface down to 800 m.

(f) *Other current variations: Turbulence*

When the periodic constituents of the currents, due to tides, internal waves or inertia oscillations, have been removed, the residual current still shows variations in many cases. EKMAN (1953), in his analysis of the *Armauer Hansen* 1930 results, distinguished between " variable mean motion " – a gradual change in the residual current over several days' observations – and variations on a time scale of a few hours, which he termed " turbulence." He pointed out, however, that the slower variations might also be regarded as turbulence on a larger time scale. The variations on a scale of a few hours could not be attributed to ship's movements or to variations in wind, and did not occur in the same way at all depths. On the other hand, the variations were frequently similar at neighbouring levels although different for levels far apart, which led EKMAN to suggest the existence of " turbulence elements " with a vertical extent of several hundred metres.

5. CONCLUSION

A survey of the measurements which have been made shows the complexity of water movements in the oceans, and the difficulty of planning and analysing the

observations so as to be able to separate the various periodic motions, the mean current and the non-periodic variations. The need for continuing the measurements at one station for a period of the order of a week is apparent, both in order to obtain an adequate number of periods of the semi-diurnal, diurnal or other periodic constituents to determine their amplitudes and phases with sufficient accuracy and to derive a satisfactory value for the mean current. Hitherto measurements below 1,000 m have been made only infrequently, but in order to throw light on the deep water movements the measurements should be extended to the greater depths whenever possible. The measurements which have been described have been made by current meters suspended from an anchored ship and it has been necessary to estimate the effects of movements of the ship on the measurements and to eliminate them. It seems very desirable that this possible source of error should be removed, especially when the measurements extend to the deeper layers, where the currents may be expected to be very small. It may prove possible, with the development of new instruments and methods, to make the measurements in such a way that they are quite independent of the movements of a ship.

I wish to record my thanks to Dr. G. E. R. DEACON, who suggested that this survey should be made, for his helpful advice and criticism in the preparation of the paper.

National Institute of Oceanography, Wormley, Surrey, England.

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On the sounding of trenches

ROBERT L. FISHER

Summary—During 1952-53 the Scripps Institution of Oceanography research vessels *Horizon* and *Spencer F. Baird* made extensive bathymetric investigations of the Tonga and Japan Trenches. The greatest minimum travel-time recorded from the Tonga Trench corresponds to a depth of 5,814 $\pm$ 15 fathoms (10,633 $\pm$ 27 metres), corrected. If this value were accepted as the true depth, it would be the deepest sounding yet recorded from the Southern Hemisphere, but careful study of the records indicates that the actual maximum depth in this area is probably at least 5,900 fathoms. This measurement was made by recording the echoes from the explosion of a small charge with a hydrophone and pen oscillograph. The principal sources of error in this method are evaluated; errors in interpretation of such sonic soundings are probably many times as great as the errors in measurement. Soundings in the Japan Trench were recorded with a high-frequency echo-sounder. Results of this investigation in the Ramapo Deep indicate a maximum depth of about 5,250 fathoms (9,600 metres), corrected.

PART 1

Exploration of the Tonga Trench by *R/V Horizon*

A. INTRODUCTION

IN DETERMINING and in discussing the configuration of the sea-floor it is necessary to distinguish rather carefully between the terms "sounding" and "depth." A sounding, at a point at sea, is an interpreted measurement expressed as a depth and appears as a depth notation on nautical charts. The depth at such a point, however, is the vertical distance from the sea surface to the bottom and its magnitude is in no way dependent on sounding measurements.

In attempting to determine depth various measurements are made; for example, travel-time in sonic sounding, length in wire sounding, or temperature and/or pressure. In sonic-souding, the travel-time is multiplied by the velocity of sound in sea water and the product is expressed as a length. The echo-sounder generally incorporates this step in its recording system; the travel-time is multiplied by a constant nominal value for sound velocity and the recorder scale is read in terms of length. The echo-sounder may detect all bottom echoes from within its beam pattern; the first arrival, which is usually accepted as the sounding, is merely the reflection from the nearest part of the sea-floor. When the bottom is nearly horizontal and of small relief there is little error introduced by taking the first arrival in computing the depth; if the bottom is irregular this error may be very great. The following discussion attempts to show how an analysis of the entire echo train may permit a truer estimate of depth in regions of moderate to large bottom relief.

B. DESCRIPTION OF METHOD AND DISCUSSION OF SOUNDINGS

In December, 1952, and January, 1953, during the Scripps Institution of Oceanography CAPRICORN Expedition, the research vessels *Horizon* and *Spencer F. Baird* made 24 lines of soundings across the Tonga Trench, between latitudes 14°30′S and 26°15′S. The greatest depths (FISHER and REVELLE, 1954) were found about 180

miles south of Tongatabu, the largest island of the Tongan Archipelago (Fig. 1, inset). It may be significant that the greatest depths recorded during this fairly detailed bathymetric exploration of the Tonga Trench lie very near the only abrupt change in trend of the trench axis, from N 25°E to about north-south at 24°15′S.

Nineteen of the crossings were made by *Horizon*, which was equipped with a high-frequency EDO echo-sounder modified to permit shoal scale operation on all ranges so that the instrument could be read to 10 fathoms even at great depths. Water noise, however, prevented the consistent recordings of depths greater than 4,000 fathoms; in such deep areas soundings were logged from audible returns. In all deep areas a standard NMC-2 echo-sounder was employed to give a supplementary record; the two fathometers gave comparable depth readings in all cases.

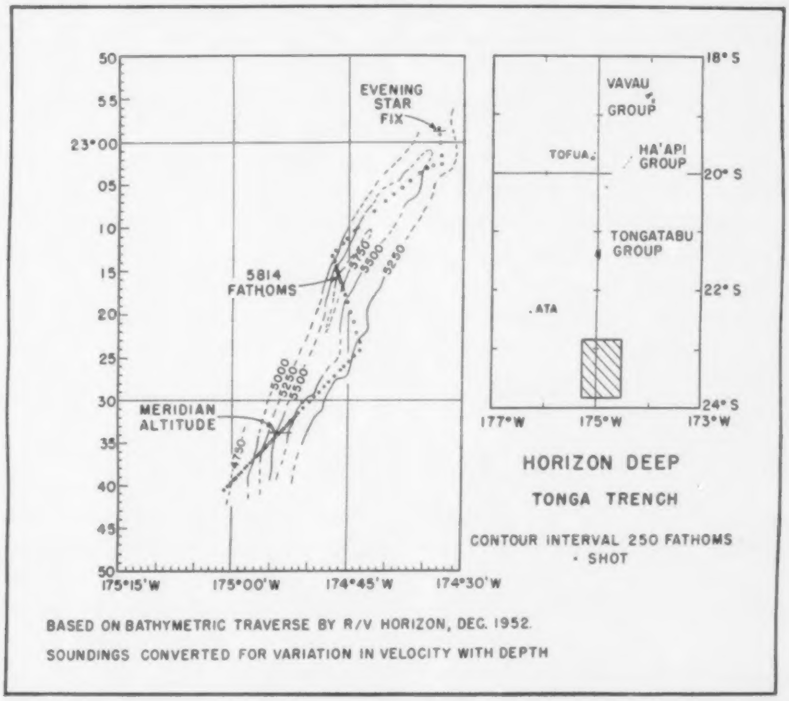

Fig. 1. Topography of the *Horizon* Deep, based on shot-echo intervals expressed as equivalent depths.

The deepest portion of the Tonga Trench explored by *Horizon* was sounded by recording the echoes from explosions set off at shallow depths. As the ship proceeded at about 7·5 knots, half-pound demolition blocks with 14-inch fuses were dropped overboard at 3 to 10 minute intervals. The charge detonated at a depth of 10 to 12 fathoms; the firing-mark and echo-train were received on the echo-sounder hydrophone and recorded on one channel of a pen oscillograph. Timing marks were placed on the record at one-second intervals by means of a break-circuit chronograph. Sounding velocities, based on temperature measurements and salinities of water samples collected by *Baird* 200 miles north of *Horizon*'s position, were

computed from tables compiled by KUWAHARA (1939). Samples were collected to 7,000 metre (3,800 fathoms) depth along the trench axis, and the computed velocity curve extrapolated to 5,000-6,000 fathom depths. The positions of the deep soundings were determined by dead reckoning between morning and evening star fixes, supplemented by a latitude from meridian altitude at noon.

Fig. 1 is a contoured plot based on the observed travel times of first arrivals as determined by the explosion-oscillograph method, expressed as equivalent depths. This plot has not been corrected for slope-echo effects; in preparing the chart each computed depth was plotted at the ship's position corresponding to the time the measurement was made. As in several other trenches, notably the Acapulco and Aleutian Trenches, the nearshore wall (in the Tonga Trench the western wall) is generally steeper than the offshore wall.

The deepest sounding shown on Fig. 1, 5,814 fathoms $\pm$ 15 fathoms, lies at latitude 23°15·5′S, longitude 174°46·5′W, with a possible error in position of two miles. In accordance with recent practice in deep-sea floor nomenclature (WISEMAN and OVEY, 1953, p. 14), it is here suggested that this sounding be called the Horizon Depth, after the exploration vessel. WÜST recently (1950-51, p. 213, and 1952, p. 114) has reviewed the greatest depths yet reached by echo and wire soundings. From his compilation the Horizon Depth, Tonga Trench, exceeds the Galathea Depth, Mindanao Trench, by about 50 fathoms and ranks second to the Challenger Depth, Marianas Trench, among the deep areas discovered to date. As has been pointed out by FISHER and REVELLE (1954) and as will be demonstrated in detail in the following section, the maximum depth traversed by *Horizon* was probably at least 5,900 fathoms.

C. EVALUATION OF SOUNDING ERRORS IN THE EXPLOSION-OSCILLOGRAPH METHOD

The explosion-oscillograph method outlined above eliminates sounding errors arising from frequency fluctuations or mechanical errors in the echo-sounder. However, the soundings obtained are subject to several errors of reading, timing and interpretation, so that a critical evaluation of the magnitude of such errors is required.

(1) *Reading and correcting the oscillograph records*

At the oscillograph paper speed employed (about 2·5 cm/sec) the shot record can be marked and read to an accuracy of better than 0·01 second. The shot-echo interval is the sum of two such measurements, plus a long intermediate period bounded by time marks, the total being rounded off to the nearest hundredth of a second. Since a time interval of 0·01 second corresponds to a depth difference of 4·2 fathoms, an error of less than 10 fathoms in the sounding may be introduced.

Since the charge explodes at shallow depth several hundred feet behind the ship, the firing-mark recorded at the ship is late and the shot-echo interval recorded is several hundredths of a second too short. A correction factor, constant so long as the ship's speed, the firing time and the shot depth remain constant, must be added to the interval as recorded. In *Horizon*'s investigation this correction was computed in the following manner:

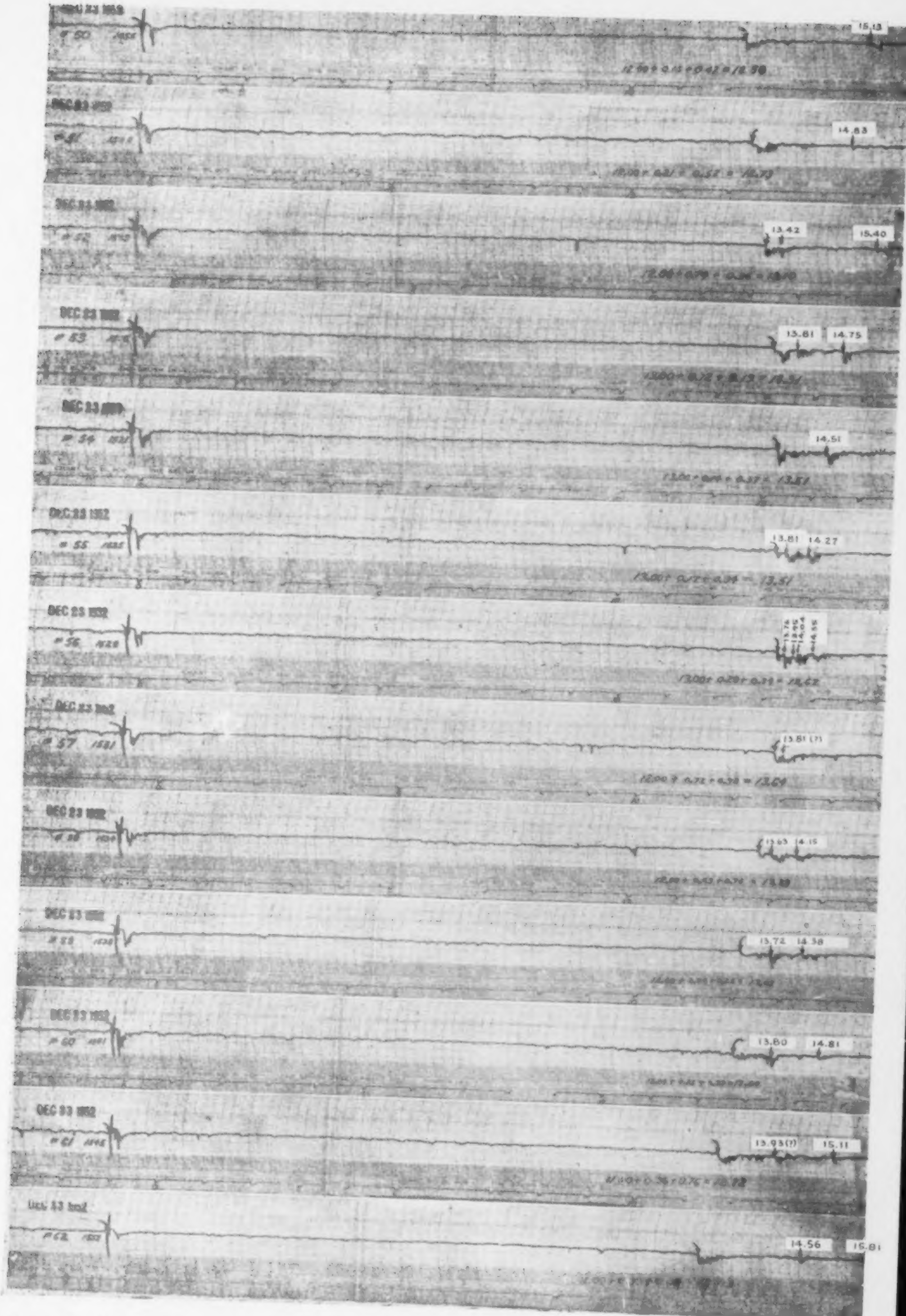

PLATE 1. Oscillograph records 50-62, from the shot-profile yielding the deepest Tonga Trench sounding

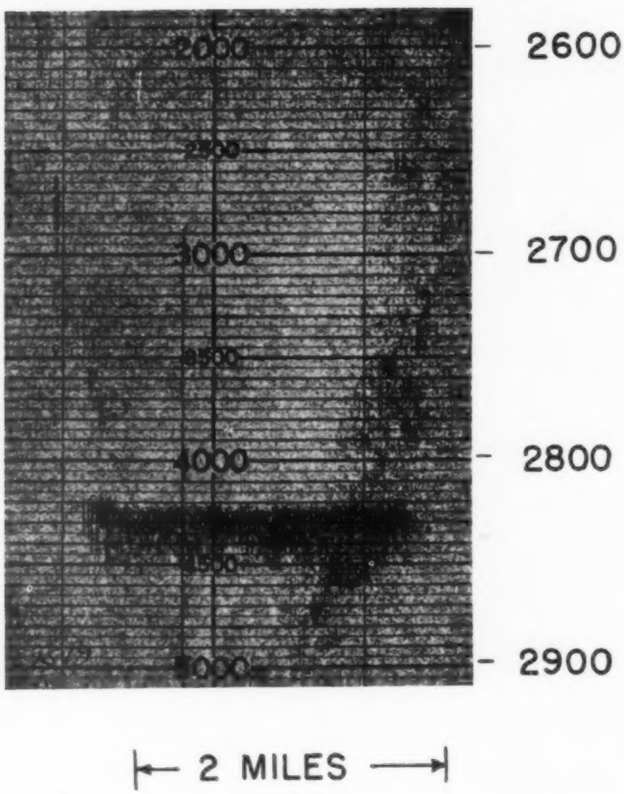

PLATE 2. Portion of fathogram from the Acapulco Trench. Strong echo from flat bottom at 2,820 fathoms.

if D = the horizontal distance the ship moves after dropping the charge and prior to the shot,
d = depth at which the charge detonates,
c = mean sound velocity between the surface and the charge depth,
T_r = travel time recorded,
T_{s-s} = travel time, surface to surface,

then

$$T_{s-s} = T_r + \frac{d}{c} + \frac{\sqrt{D^2 + d^2}}{c}$$

With a shot depth, d, of about 65 feet, a horizontal displacement, D, of 435 feet (35 seconds at 7·5 knots), and a mean sound velocity between the surface and depth of shot of 5,030 feet/second (based on bathythermograph measurements), the correction factor to be added to the recorded shot-echo interval is 0·10 (0) second.

(2) *Variation in the timing mark*

Error due to daily gain or loss in the chronometer is negligible. The magnitude of the error in the oscillograph circuit is not known, but total error in timing is almost certainly less than 0·01 second.

(3) *Errors in the sounding velocities applied*

Since the sounding velocities used in computing water depth from recorded travel times were based on hydrographic data from a very deep cast in a comparable environment only 200 miles distant, these velocities as applied are probably accurate to one part in a thousand, in this case corresponding to an uncertainty in depth of 5 or 6 fathoms. About 3/4 of the travelled path lies in water which is nearly isothermal and isohaline. Under such conditions sound velocity variation is almost entirely a function of pressure, so that extrapolating the sounding velocity curve 2,000 fathoms beyond the deepest temperature-salinity observations introduces no significant error.

(4) *Travel path error*

A negligible error is introduced by assuming that the depth, or vertical path, is one-half the travelled path. If the water depth is 34,500 feet (5,750 fathoms) and the horizontal distance from shot position to the ship's position when receiving the echo is 435 feet, then one-half the travelled path $= \sqrt{(34{,}500)^2 + \left(\frac{435}{2}\right)^2} = 34{,}500$ $(1{\cdot}00002) \approx 34{,}500$ feet.

(5) *Recognition of significant returns*

In the interpretation of the shot records two very important assumptions are :

(*a*) the marked return is a bottom echo, not spurious noise, and

(*b*) the bottom echo from directly beneath the ship, if a first arrival, did not go unmarked.

Plate 1, a reproduction of 13 consecutive shot records from the profile yielding the deepest soundings, furnishes clear evidence on assumption (*a*). On all of these

shot records the disturbances marked as echoes are much longer and stronger than any of the short duration pulses occurring randomly along the records. The marked returns show a consistent increase in shot-echo interval to shot number 57 and then a decrease to shot 62; there are no stray returns. On each record the minimum echo time has been taken for computing the sounding; on several records (notably 53 and 59) a stronger later pulse is recorded.

With regard to assumption (*b*), the author and his colleagues have often observed that a rather flat depression, such as a trench bottom partly filled by sediments, generally gives a stronger return on the echo-sounder than would a steep, rough and possibly rocky slope such as a trench flank. HESS and BUELL (1950, p. 403), in a detailed discussion of sounding data from the Mindanao Trench and the Ramapo Deep, reached the opposite conclusion and maintain that the stray, especially deep soundings logged by the *Emden* and *Ramapo* were actually echoes from neighbouring slopes farther from the ship than was the true bottom.* The writer agrees fully that such inconsistent deep soundings are probably side echoes and that the echo from directly beneath the ship came back earlier and was missed. However, the more characteristic relative strength of echoes from a trench bottom and a trench slope is shown in Plate 2, a portion of a fathogram recorded in the Acapulco Trench. Here the very weak echoes from the trench walls migrated downward through the strong echo from the nearly flat trench bottom. No fathogram of comparable quality is available for the Tonga Trench, but the same relationship between echo strengths has been observed in the Tonga, Aleutian, Kurile-Japan and Acapulco Trenches and in the Cedros deep on recent Scripps Institution expeditions. Furthermore, echo sounding results from the recent investigations of the Marianas Trench by H.M.S. *Challenger* support this interpretation. According to GASKELL, SWALLOW and RITCHIE (1953, p. 61),

> " The echo was sometimes lost for a few consecutive transmissions, but was always loud and clear at the deepest part of the trench. The weak echo may come from steep slopes, and soundings taken at one-minute intervals do sometimes show sudden changes of 50-70 fathoms after a flat bottom stretch of several minutes duration."

It is probable that the above relationship between the strength of side and bottom echoes from trenches holds for impulses from explosions as well as for the higher frequency fathometer pulses. Similar records were obtained on *Horizon* with an oscillograph used alternately to record reflections from explosions and fathometer ping reflections between shots. *Spencer F. Baird* recorded fathometer ping returns by oscillograph to obtain more accurate deep soundings than could be logged audibly, but the quality of such records is poorer than that of the records from explosions.

(6) *Slope echoes*

The possibility that some of the echoes marked on Plate 1 return from neighbouring shallower portions of the sea floor rather than from directly beneath the ship was examined by describing arcs, of radius equal to the indicated sounding, about the corresponding position of the ship. The effect of such echoes would be to mask true bottom and to make the trench appear narrower than its actual width. This

* However, in a personal communication, HESS agrees that as a rule echoes from the flat floor of a trench are usually stronger than from the walls.

sounding line runs at a large angle (about 48°) to the trend of the trench bottom, so that slope echoes are considered to come chiefly from ahead of or behind the ship rather than from either side. From this analysis it is probable that the first returns on shot records 51, 52, 53, 54, and 55 come from farther east, on the trench wall, than the ship's indicated position. First returns on records 58, 59 and 60 probably are reflections from the west wall of the trench. The evidence from such an analysis

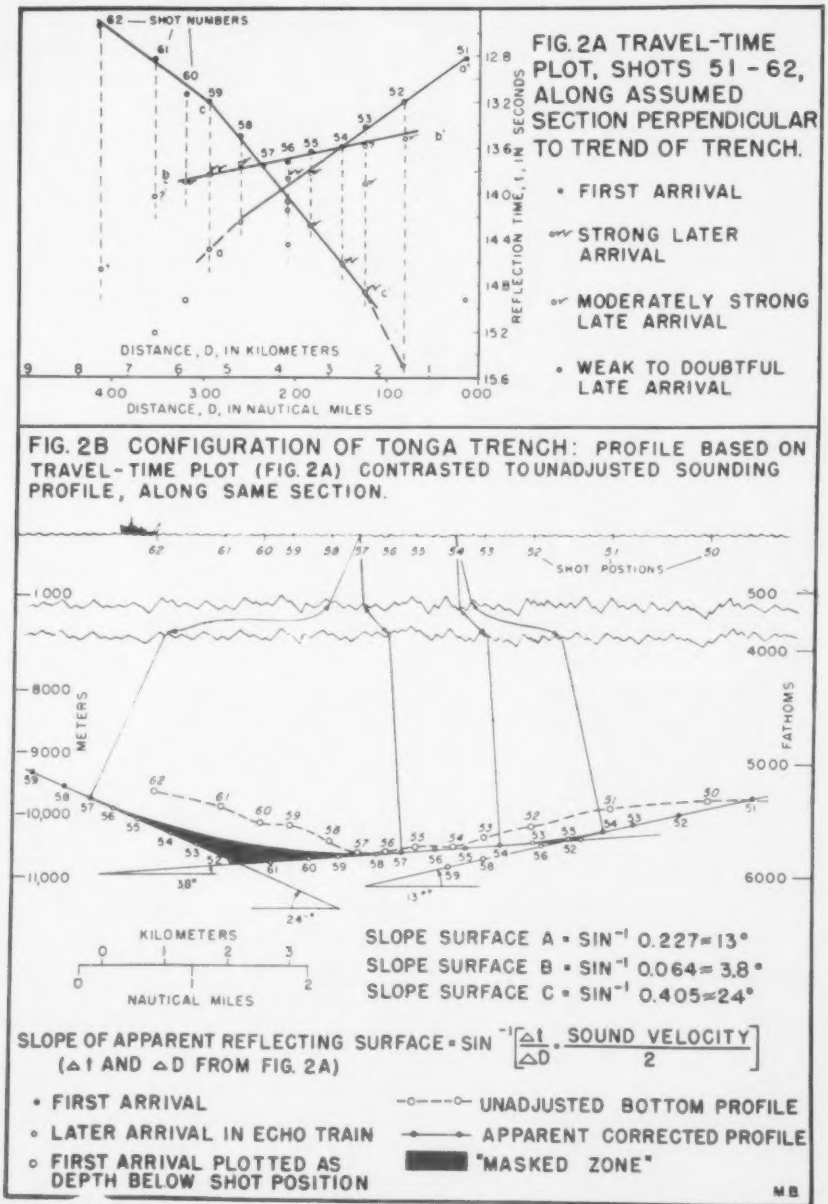

Fig. 2. (A) Travel-time plot and (B) topographic interpretation from shot records 51-62.

is inconclusive for the first return on record 57, corresponding to the 5,814 fathom sounding, and record 56. If these first arrivals too are slope echoes, as well they may be, the trench is deeper than 5,814 fathoms.

Much more rewarding, and possibly less misleading, is a detailed examination of the records of the echo trains themselves. Fig. 2a is a travel-time plot of all readable echoes from shots 50-62. In preparing this plot the shot positions along the ship's track were projected on a line normal to the trend of the trench as shown in Fig. 1, and the distance along the assumed section was measured from an arbitrary point just east of the position of shot 50. A line *a-a′* may be fitted, by the usual method of least squares, through the plotted first arrivals from records 51, 52, 53 and 54, and later arrivals on records 55, 56 and possibly 58 and 59. A similar line, *b-b′*, is fitted through first arrivals on records 54, 55, 56, 57 and possible later arrivals on 52, 53, 58, 59 and 60. A third line, *c-c′*, has been fitted through the first arrivals from records 57, 58 and 59, and good later arrivals on records 53, 54, 55 and 56. The echoes joined by a line such as *a-a′* are assumed to return from a single reflecting surface, parallel to the trend of the trench. If such a correlation is accepted, the dip of the apparent reflecting surface may be computed from the slope of the travel-time line and the sound velocity. From Fig. 2a it appears that three major reflecting surfaces may be proposed: two steep trench walls and a gently-dipping, westward-sloping trench bottom. In the case of shots 54 and 57, the first arrivals may return from two planes simultaneously, or possibly a second echo returns too soon after the first arrival to be resolved. This simplified interpretation neglects changes in trend as well as small irregularities on the trench walls; such departures from an ideal surface would be present, of course, and would help account for the scatter in the travel-time on any line. Variation in ship's speed may also introduce error into the travel-time plot.

In Fig. 2b the apparent reflecting surfaces are plotted as segments of a trench profile. Two lines were plotted tangent to a circle of radius equivalent to $5{,}814 \times 6$ feet, centred at shot position 57: one, representing the west wall, dips easterly at 24°; the other dips westerly at $3{\cdot}8^\circ$. Similarly, a line dipping westerly at 13° was drawn tangent to a circle of radius equivalent to $5{,}755 \times 6$ feet, centred at shot position 54. The $3{\cdot}8^\circ$-dipping line is also tangent to this second circle. Along each line the most probable points of reflection (for minimum reflection travel-time) for each shot have been determined by dropping a perpendicular to the line from the corresponding shot position. The probable point of reflection of the first echo arrival from each shot is shown by a solid circle, the possible reflection points of later arrivals from each shot are shown as open circles. An unadjusted bottom profile (dashed line in Fig. 2b) with first-arrival travel-time expressed as water depth plotted directly below the corresponding ship's position, has been projected along the same section, normal to the trend of the trench.

Several conclusions regarding the interpretation of echo-sounding results may be drawn from Fig. 2b. In constructing the trench profile, based on the travel-time plot of Fig. 2a, it has been assumed that the first arrival on record 57 is the sum of the reflections from the west wall and the gently-sloping bottom, arriving simultaneously, and the first arrival on record 54 comes from the trench bottom and the east wall simultaneously. The appearances of the first breaks in the echo trains of records 54 and 57 are suggestive in this connection; they are sharper and stronger

than the first breaks on adjacent records. If such nearly-simultaneous arrivals are present, there is in each case a " masked " zone between the two reflection points. With a broad beam receiver, reflections from the bottom lying within the zone never could appear as first arrivals, though possibly, especially in the case of a basin partly filled by sediment, they would arrive as strong later reflections. Only by using a narrow-beam echo-sounder could the vertical distance to bottom within the " masked zone " be determined. An approximate maximum depth may be obtained by projecting to intersection the apparent reflecting planes. From the data as interpreted here the greatest depth along this profile is probably at least 5,900 fathoms (10,800 metres), vertically beneath a point between shot positions 60 and 61 at the intersection of the 24°-dipping and 3·8°-dipping planes. Again it must be emphasized that the reality of this depth, both as to magnitude and position, is chiefly dependent on the validity of the travel-time plot. Small changes in the values computed for the slopes make appreciable changes in this indicated depth. In view of the small number of observations included in the slope determinations no value for the probable error in this depth is proposed. Sedimentary fill would reduce the depth; a steepening of the trend walls downward, as is sometimes observed, would increase it. Neither of these conditions can be detected here.

The horizontal distance from the plotted position of the deepest sounding, directly below shot position 57, to the point on the assumed west wall giving the same reflection time is 2·8 miles. It is entirely possible, however, that this maximum sounding is based on a reflection from the bottom on either side of the ship's track.

From the profiles here developed the maximum difference in depth as computed from the travel-time-slope analysis and depth based on a single travel-time record plotted beneath the shot position is about 450 fathoms, at a point between shot positions 60 and 61. The difference between the two methods of interpretation is in this case about 30 times as great as the uncertainty in the measurement of the travel time.

D. CONCLUSIONS

The assessment of the errors involved in the explosion-oscillograph method of sounding has been developed in detail to permit setting limits of error to the deep soundings taken by *Horizon*. Aside from questions of interpretation, the greatest uncertainties lie in reading the oscillograph records and in the sounding velocities applied. Under the conditions of the *Horizon* soundings, a maximum error of 10 fathoms from the former and 5 fathoms from the latter seems reasonable, so that the longest travel time for a first echo from the Horizon Depth corresponds to 5,814 $\pm$ 15 fathoms. Such a degree of precision supports the conclusion reached by ADAMS in evaluating a nearly-identical method (ADAMS, 1942, p. 553):

> " The data are inconclusive but seem to indicate that sounding with bombs should give results within the specified accuracy of 99·5 per cent for depths of 3,000 fathoms or greater."

From the discussion of the interpretation of the sounding results, however, it is plain that this sounding is not a valid maximum for the region of the Horizon Deep; it is merely a minimum interpreted value for the reflection travel-time at one shot position. A better estimate is obtained by analysis of the echo trains of all shots along the profile. From this it is evident that the deepest point traversed by *Horizon* was probably at least 5,900 fathoms.

PART II

Exploration of the Ramapo Deep by the *Spencer F. Baird*

THE area of the Ramapo Depth (HESS and BUELL, 1950, p. 405) in the Japan Trench southeast of Honshu was visited by the Scripps Institution of Oceanography research vessel *Spencer F. Baird* during the 1953 Trans-Pacific Expedition. The primary

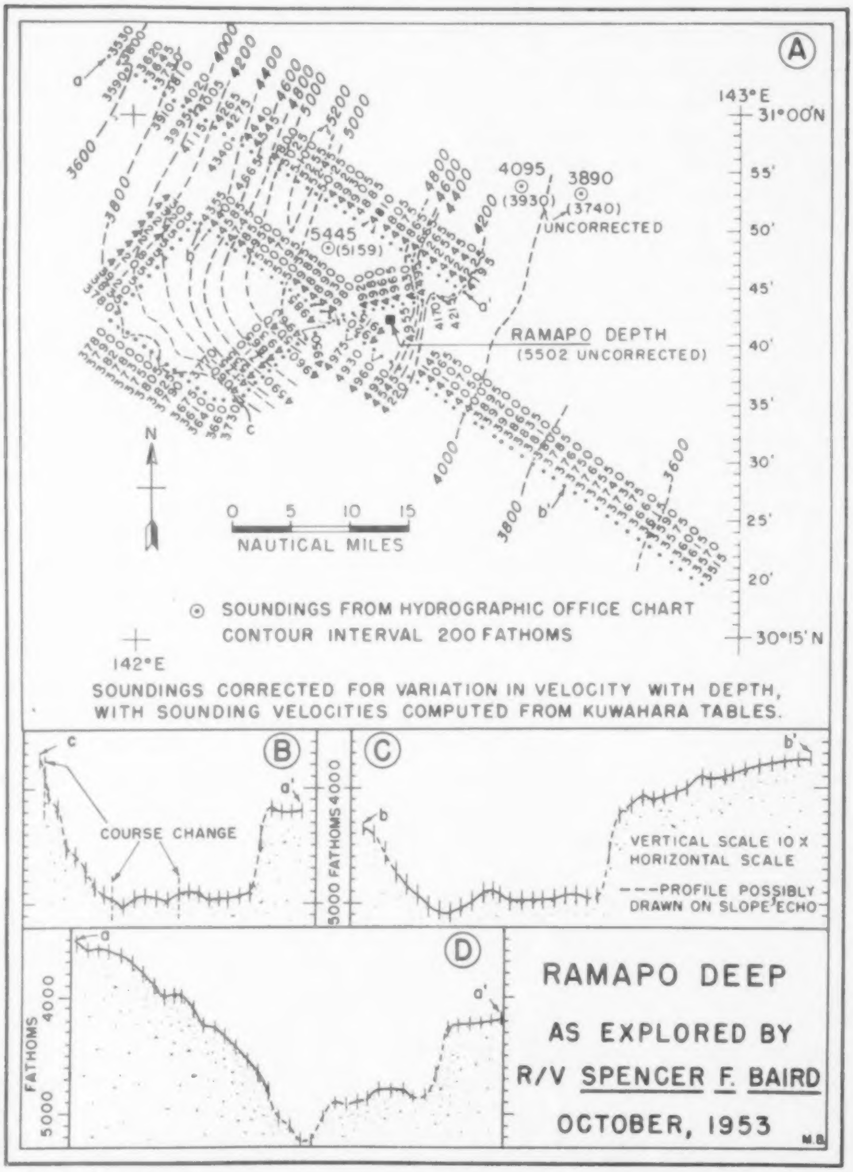

Fig. 3. (A) Sounding lines run by *Spencer F. Baird* near the Ramapo Depth and (B, C, D) unadjusted bottom profiles with soundings plotted as depths.

objectives of the expedition were hydrographic and biological investigations, but some time was available for examining the sea-floor topography in this area.

Like *Horizon*, *Spencer F. Baird* is equipped with a high-frequency EDO echo-sounder modified to allow shoal-scale stylus and recording speeds on all ranges. A detailed trace of the bottom topography was obtained at the greatest depths, although the echo was occasionally lost on steep slopes. The echo-sounder was operated continuously. Although several abrupt changes in level were noted, the soundings varied consistently; there were no single deep soundings flanked by much shallower readings. During the Ramapo Deep exploration the frequency of the current to the echo-sounder motor remained constant at 60·4 cycles per second; the soundings as read have been multiplied by 60·0/60·4 to correct for the deviation from standard frequency. Due to mechanical errors of the echo-sounder the readings recorded by stylus on the 4,200-4,800 and 4,800-5,400 fathom scales are 20 to 30 fathoms shoaler than the soundings obtained by recording on an oscillograph the ping and echo received by hydrophone. Therefore, 25 fathoms was added to the observed soundings to get corrected nominal (assumed sound velocity of 4,800 feet/second) soundings.

Positions of the soundings were obtained by LORAN and by back-tracking from radar and visual cuts on the small islands of the Nanpo Shoto 125 miles to the west. The maximum error in position is 6 miles; the probable error is 3 to 4 miles.

Nominal soundings were corrected by computation of sounding velocities from the Kuwahara tables. *Spencer F. Baird* made several 2,000-3,000 metre hydrographic casts in the southern Japan Trench and found practically no lateral variation in temperature and salinity at depths greater than 545 fathoms (1,000 metres). Therefore sounding velocities for the Ramapo Deep were computed from temperature and salinity measurements from a deep (3,440 fathom) cast 70 miles north in the trench.

Fig. 3a is a contoured plot of the corrected soundings from the *Spencer F. Baird* traverses only. The soundings were plotted at 5-minute intervals along the track, but intermediate one-minute soundings were considered in drawing the contours. An abrupt change in trend of the trench axis from north-northeast to nearly south-east, or an abrupt narrowing of the trench, can be postulated from the *Baird* soundings. A good crossing of two *Baird* lines was obtained at 4,955 fathoms. The Ramapo Depth, shown on old Hydrographic Office charts as 5,502 fathoms uncorrected, lies between two 4,700 fathom (uncorrected) *Baird* soundings and is, as HESS and BUELL (1950, p. 405) maintain, of very doubtful validity. In the region explored by *Spencer F. Baird* the deepest sounding shown on recently published U.S. Hydrographic Office charts, 5,159 fathoms (5,445 corrected), is 190 fathoms deeper than the deepest *Baird* sounding, 5,255 fathoms (9,611 metres, at 30°54-1/2′N, 142°16-1/2′E). The *Baird's* traverse furnishes no information as to the validity of this sounding.

Figs. 3b, 3c, 3d are sounding profiles based on *Spencer F. Baird* soundings only. All three show an abrupt break on the offshore side of the trench, from a general level of 4,000-4,200 fathoms down to a general level of 4,800-5,000 fathoms. The knolls on this deep surface may be peaks or ridges partly buried by sediments slumped from zones higher on the east flank. The deepest soundings on each profile occur near the steep west flank of the trench, in an elongate basin 200-300 fathoms deeper than the 4,800-5,000 fathoms plain noted above. Such a deep " inner gorge " was found also on several of the deepest Tonga Trench crossings, and may be characteristic of such very deep trenches. The deepest *Spencer F. Baird* soundings

on profile *a-a'*, may be slope echo returns, with the trench bottom actually deeper than 5,245-5,255 fathoms. The echo-sounding record for this crossing is not of sufficient quality to permit resolution of the echoes and construction of the apparent reflecting surfaces, as was attempted from the shot records from the Tonga Trench in the preceding discussion.

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Scripps Institution of Oceanography, La Jolla, California, U.S.A.

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Atmospheric pressure changes and gas solubility

DAYTON E. CARRITT

Summary—The calculation of percent saturation, and similar quantities, for oxygen and nitrogen dissolved in sea water is done under the assumption that the gases were dissolved from a normal atmosphere with a pressure of 760 mm Hg. It is pointed out that the seasonal changes in atmospheric pressure that occur over the ocean surface are sufficient to impart measurable changes in gas solubility, being approximately 0·3 ml/l for oxygen and 0·6 ml/l for nitrogen. The possibility of using the nitrogen change as a seasonal tag is mentioned.

THE results from the analyses for dissolved atmospheric gases in sea water, with the exception of carbon dioxide, are treated in one of two ways. The results expressed in concentration units are either used directly, or they, together with appropriate saturation tables, are used to calculate *percent saturation*, *deficit* as is frequently done with oxygen data, or *apparent oxygen utilization* a term defined and used by REDFIELD (1942).

When calculating departures from saturation for sub-surface ocean samples the following assumptions are always tacitly connected with the computation.

(1). When last in contact with the atmosphere the water actually became saturated with atmospheric gases.

(2). The temperature and salinity have not changed since the sample was last in contact with the surface, and

(3). Saturation was from a normal atmosphere with a pressure of 760 mm (1013.3 mb).

The first two assumptions are frequently stated when these calculated quantities are reported. The third assumption usually is completely ignored. It is obvious that the third condition is always implied in such calculations when it is recalled that all saturation tables, such as oxygen saturation by FOX (1909) and nitrogen and argon saturation by RAKESTRAW and EMMEL (1937-1938), have been constructed from measurements either made at or corrected to 760 mm total pressure.

The purpose of this note is to point out the variability in the solubility of oxygen and nitrogen when saturation is from an atmosphere in which the pressure may vary over the range normally encountered over certain ocean areas.

Cyclic variations in atmospheric pressure over ocean regions, especially in high northern latitudes, occur with a maximum in summer and a minimum in winter. The difference between the two seasons is 25 to 30 mb (19 to 23 mm Hg). Much larger changes can be noted during the passage of storms, but since these changes are of relatively short duration and occur in a much less predictable manner, they will be neglected here.

Gas solubility at these various pressures can be calculated if one assumes that the gas obeys Henry's Law, that is, that the quantity of dissolved gas is directly proportional to the partial pressure of the gas in the gas phase. As an example, it will

be found that for water at 0°C and chlorinity 20‰ the saturation concentration of oxygen at 740, 760 and 765 mm, being winter, normal (by definition), and summer pressures respectively, will be 7·80, 7·97, and 8·14 ml/l, a maximum difference of 0·34 ml/l. The figures for nitrogen under the same conditions are 13.88, 14·21, and 14.53 ml/l, a maximum difference of 0·65 ml/l. In both cases the differences are well within the limits of present day analytical methods. If saturation occurs in warmer or more saline water, the differences will be somewhat smaller but, in all cases likely to be found in the oceans, are of measurable magnitude.

Transferring these considerations to observations obtained from subsurface samples in the oceans, it becomes apparent that because it is not possible to know what the pressure was over the sea surface at the time the sample left the surface, all calculated departures from saturation based on a 760 mm atmosphere should be surrounded by a band of uncertainty, and the magnitude of this band will correspond to the changes in gas concentration that would be produced by normal pressure fluctuations over the sea surface. In the case of calculated oxygen deficit or apparent oxygen utilzation the uncertainty can be expected to be 0·2 to 0·4 ml/l if sea level pressures, in the regions in which sub-surface waters are " formed," vary in the range 740 to 765 mm.

Unfortunately existing oxygen data, although plentiful, are of little help in testing the existence of the effect just described. The changes in the concentration of dissolved oxygen produced by biological activities are usually larger than those that could be realized by pressure changes.

The existing measurements of dissolved nitrogen in sea water, while few in number do nevertheless give assurance that the pressure fluctuations over the sea surface are reflected in changes in gas concentration. The data of RAKESTRAW and EMMEL (1937-1938) appear to be the only existing measurements in which dissolved nitrogen is distinguished from dissolved " inert " gas. Their measurements are of 85 samples obtained at 6 stations in the North Atlantic. An analysis of these data, under the assumption that biological processes have not altered the concentration of dissolved nitrogen permit the following observations that are believed pertinent to the present discussion.

(1). The mean percent saturation (760 mm atmosphere) for the 85 determinations is 100·4%. This suggests that if the departure from 100% saturation of each of the samples (the range is 108 to 95%) is a reflection of existing atmospheric pressure over the sea surface at the time each sample left the surface, the mean pressure must have been very nearly 760 mm.

(2). Of the 85 analyses reported, 80 fall within the range to be expected if saturation occurred from atmospheres with pressures in the range 740 to 765mm and at *in situ* temperature and salinity. The remaining five analyses are all greater than 100% and are for samples taken at depths of 40 m or less. That these five samples all show an excess of nitrogen and are from shallow depths suggests that they may have been contaminated by bubbles of atmospheric gas dragged from the surface as the Nansen bottle was lowered, there forced into solution by the increased pressure, and the resulting homogeneous solution not completely flushed by the time the Nansen bottle was closed. This effect would naturally be minimized in samples taken at greater depths as the Nansen bottles

would have been below the surface for a greater length of time, thus providing the opportunity for more thorough flushing.

(3). Two stations from RAKESTRAW and EMMEL (1937-1938) have been plotted in Fig. 1. The abscissa has been expressed both as percent saturation as reported by the authors (referred to 760 mm total pressure) and as " equivalent pressure." The latter is the pressure that would have given the same concentration of gas found by RAKESTRAW and EMMEL, had saturation (100%) occurred at 3°C and chlorinity 19‰, approximately mean conditions for the deeper samples. Because of the temperature and chlorinity dependance the " equivalent pressure " scale is only approximate and has been included only as a means of orienting the order of magnitude of the pressure range that might have been involved. These two stations form a band within which all other data fall (except the five samples previously mentioned).

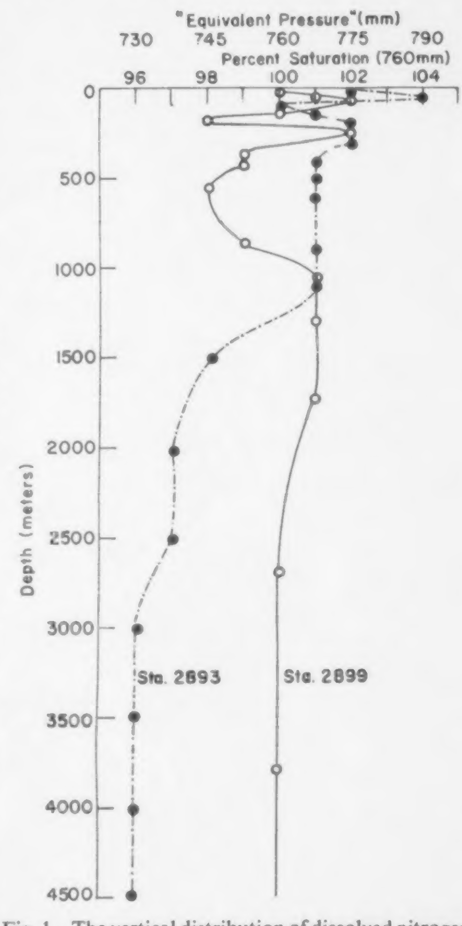

Fig. 1. The vertical distribution of dissolved nitrogen in two stations in the North Atlantic. Data from RAKESTRAW and EMMEL (1937-1938).

" Equivalent pressure " is that pressure that would have given the same concentration of nitrogen reported by the authors if saturation (100%) had occurred at 3°C and chlorinity 19‰. It is only an approximate scale because of the temperature and chlorinity dependance of nitrogen solubility.

Two features should be noted. First, the relative homogeneity, on the percent saturation scale, of large portions of the water column at each station is striking. This is particularly noticeable for station 2893 where the seven bottom samples (1500 to 4,500 m) vary from 96 to 98% and the top eleven samples vary from 101 to 104% and ten of these are in the range 101 to 102%. Two other deep stations, while not as complete as those shown in Fig. 1, exhibit the same feature. Second, the spread of all the data fall within an " equivalent pressure " band that is not unreasonable for atmospheric pressures over the sea surface.

This of course does not rule out the existance of other systems which could alter the percent saturation (760 mm) of dissolved nitrogen. The only point to be made here is that an analysis of existing data does not contradict the hypothesis that atmospheric pressure fluctuations over the sea surface are reflected in measurable changes in the concentration of dissolved atmospheric gases.

There is one piece of speculation that can be added here, with the note that it is admittedly highly speculative and at best of only limited forseeable application. It is that in regions in which bottom or deep water is thought to be formed year round, the seasonal atmospheric pressure fluctuations may tag the water with respect to dissolved nitrogen, thus affording a means of estimating the age by the number of cycles observable, and the current velocity by the distance between nodes or antinodes, of these waters.

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Contribution No. 20 *from The Chesapeake Bay Institute. Results of work carried out for the Office of Naval Research of the Navy Department, the State of Maryland* (*Department of Research and Education*), *and the Commonwealth of Virginia* (*Virginia Fisheries Laboratory*).

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Thermosteric anomaly and the analysis of serial oceanographic data

R. B. MONTGOMERY and WARREN S. WOOSTER

Summary—The pressure terms in the anomaly of specific volume of sea water are found to be negligible for hydrostatic computation in such regions as the upper layers of the equatorial Pacific Ocean. It is proposed that the anomaly of specific volume with pressure terms omitted be called *thermosteric anomaly*. This quantity is recommended for routine use in the tabulation and analysis of serial data. The systematic analysis of a vertical section can include hydrostatic computation by either of two graphical methods, one being WERENSKIOLD's method.

PRESSURE TERMS IN ANOMALY OF SPECIFIC VOLUME

THE common hydrostatic computation in oceanography is accomplished, following BJERKNES (1910), by numerical evaluation of an integral along a vertical line,

$$(\phi_2 - \phi_1)_a = \int_{p_2}^{p_1} \delta \, dp, \tag{1}$$

where $(\phi_2 - \phi_1)_a$ is the anomaly of geopotential difference between the pressure p_1 at the greater depth and the pressure p_2 at the lesser depth. The specific volume α has been separated into two terms,

$$\alpha = \alpha_{35,\,0,\,p} + \delta,$$

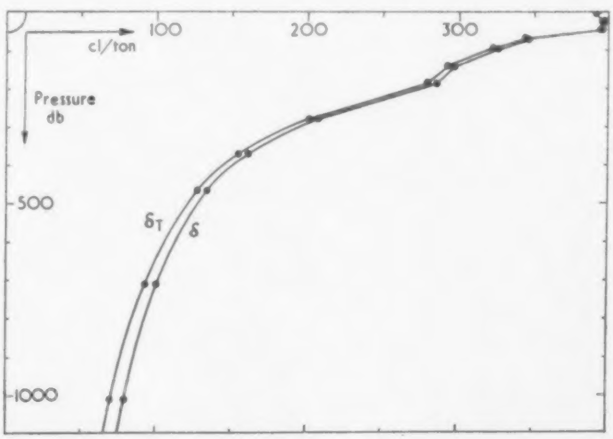

Fig. 1. Comparison of specific-volume anomaly δ and thermosteric anomaly δ_T at *Carnegie* station 148, 19 October 1929, 24°57′N, 137°44′W.

where $\alpha_{35,\,0,\,p}$, the specific volume of sea water of salinity 35 per mille at 0 C, is a function of pressure alone and δ is the anomaly of specific volume (*steric anomaly* would be shorter). The anomaly of specific volume is itself separated into six terms,

$$\delta = \delta_s + \delta_t + \delta_{st} + \delta_{sp} + \delta_{tp} + \delta_{stp},$$

Table 1. *Anomaly of geopotential difference at* Carnegie *stations, in kilergs per gram (or centimetres)*

Station	*Latitude*	*Longitude*	$\int \delta \, dp$		$\int (\delta - \delta_T) \, dp$		*Remarks*
			0 db *to* 500 db	500 db *to* 1,000 db	0 db *to* 500 db	500 db *to* 1000 db	
14	42°10′N	47°19′W	69·3	26·7	2·75	3·93	Meridional
15	38°39′N	48°48′W	92·1	68·9	4·33	10·08	section in
16	36°47′N	46°31′W	94·5	46·5	3·94	6·92	central
18	29°47′N	40°36′W	91·3	52·7	4·08	8·37	North
19	24°00′N	39°36′W	97·3	48·7	4·12	7·74	Atlantic
20	19°13′N	38°28′W	97·7	46·3	3·83	6·46	
21	15°50′N	37°56′W	82·3	42·7	3·03	5·43	
22	13°25′N	38°00′W	81·7	45·3	2·86	5·48	
23	10°50′N	37°24′W	79·8	44·2	2·71	5·02	
24	8°15′N	36°10′W	80·9	44·1	2·42	4·71	
107	14°05′N	146°06′E	165·6	50·4	3·17	4·46	Western
108	18°26′N	144°01′E	171·7	61·3	3·68	4·92	North
109	23°22′N	144°08′E	139·1	64·9	3·31	4·46	Pacific
110	26°20′N	144°24′E	133·6	68·4	3·52	4·72	
111	31°00′N	144°16′E	124·0	59·0	3·10	3·92	
112	33°51′N	141°15′E	143·3	67·7	3·58	4·98	
113	34°44′N	141°04′E	142·9	53·1	3·19	3·75	
114	36°38′N	143°34′E	86·4	46·6	2·02	2·92	
115	37°40′N	145°26′E	100·7	49·3	2·09	2·81	
116	38°41′N	147°41′E	71·5	42·5	1·24	2·70	
117	40°20′N	150°58′E	75·9	45·1	1·37	2·83	
118	42°29′N	155°24′E	69·3	44·7	1·08	2·68	
119	45°24′N	159°36′E	59·8	38·2	0·79	2·23	
120	47°02′N	166°20′E	59·7	39·3	0·80	2·26	
130	37°05′N	123°43′W	82·5	48·5	1·77	3·66	Section
131	33°49′N	126°20′W	105·2	48·8	1·95	3·48	from
132	31°38′N	128°48′W	107·8	50·2	2·00	3·56	California
133	29°21′N	132°30′W	116·2	51·8	2·37	3·56	to Hawaii
134	27°45′N	135°22′W	118·8	50·2	2·44	3·74	
135	26°39′N	139°07′W	118·2	50·8	2·44	3·60	
136	26°13′N	142°02′W	117·5	51·5	2·55	3·60	
137	24°02′N	145°33′W	131·0	51·0	2·74	3·90	
138	22°53′N	151°15′W	146·6	53·4	3·01	3·90	
139	21°47′N	155°31′W	132·4	50·6	2·65	3·86	
140	23°26′N	159°27′W	155·4	54·6	3·13	3·81	
148	24°57′N	137°44′W	123·4	50·6	2·57	3·76	Section in
149	21°18′N	138°36′W	124·2	52·8	2·60	4·16	equatorial
150	16°15′N	137°06′W	111·3	48·7	2·54	4·40	Pacific
151	12°40′N	137°32′W	90·6	50·4	2·55	4·74	
152	10°05′N	139°44′W	83·4	50·6	2·51	4·94	
153	7°45′N	141°24′W	119·2	49·8	2·66	4·77	
154	6°42′N	143°22′W	127·0	50·0	2·70	4·80	
155	4°51′N	146°46′W	135·6	49·4	2·86	4·86	
156	3°01′N	149°46′W	138·0	49·0	2·96	4·68	
157	1°48′S	152°22′W	124·4	48·6	3·06	4·64	
158	6°33′S	154°58′W	134·0	49·0	3·11	4·78	
159	9°24′S	159°01′W	142·6	48·4	3·30	4·54	

each depending on salinity, temperature, and pressure to the extent indicated by the subscripts. The last three terms are referred to as the *pressure terms*. The sum of the first three terms is determined by salinity and temperature and is here designated δ_T (SVERDRUP, 1933, uses the symbol $\Delta_{s,\,T}$), so

$$\delta = \delta_T + \delta_{sp} + \delta_{tp} + \delta_{stp}.$$

It is proposed that the quantity δ_T, heretofore nameless, be called *thermosteric anomaly*. Defined physically, thermosteric anomaly is the anomaly of specific volume (steric anomaly) that would be attained if the water were changed isothermally to a standard pressure of one atmosphere. The distributions of thermosteric anomaly and specific-volume anomaly at a typical station are shown in Fig. 1.

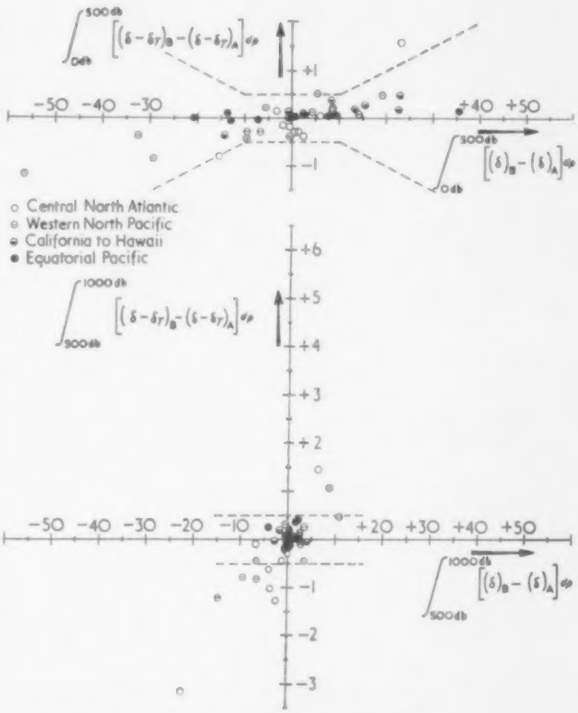

Fig. 2. Station-to-station change in thickness of the layer 0 db to 500 db (above) and of the layer 500 db to 1,000 db (below). The part of the change contributed by the pressure terms is shown as ordinate in comparison with the total change shown as abscissa. The ordinate scale is exaggerated ten times. The units are kilergs per gram (or centimetres). Data from Table 1.

It seems always to have been taken for granted that the pressure terms in the anomaly of specific volume are important. To see whether the pressure terms may be neglected for certain purposes, the *Carnegie* stations listed in Table 1 are examined, the data being taken from FLEMING *et al.* (1945). The stations were selected to illustrate a variety of situations as noted in the table.

The anomaly of geopotential difference (1) is tabulated for each station for the layers from 0 db to 500 db and from 500 db to 1,000 db. For the same pressure intervals, Table 1 also shows the integral of the pressure terms,

$$\int_{p_2}^{p_1} (\delta_{sp} + \delta_{tp} + \delta_{stp})\, dp = \int_{p_2}^{p_1} (\delta - \delta_T)\, dp. \tag{2}$$

The terms δ_{sp} and δ_{tp} were read from LAFOND's (1951) Tables VI and VII. The term δ_{stp} was found from the Hydrographic Tables of BJERKNES (1910) to be insignificant.

For the station values in Table 1, the differences between successive stations are shown in Fig. 2. It is seen that in the upper layer the station-to-station change of

the integrated pressure terms (ordinate) is always small: with the exception of one Atlantic station, this change is either less than 0·5 cm or less than 5 per cent (sloping dashed lines) of the total change of layer tnickness (abscissa). In the deeper layer the change of the integrated pressure terms is as large as 6 cm for one pair of Atlantic stations, but for all station pairs on the section from California to Hawaii and on the section in the equatorial Pacific the change is less than 0·5 cm.

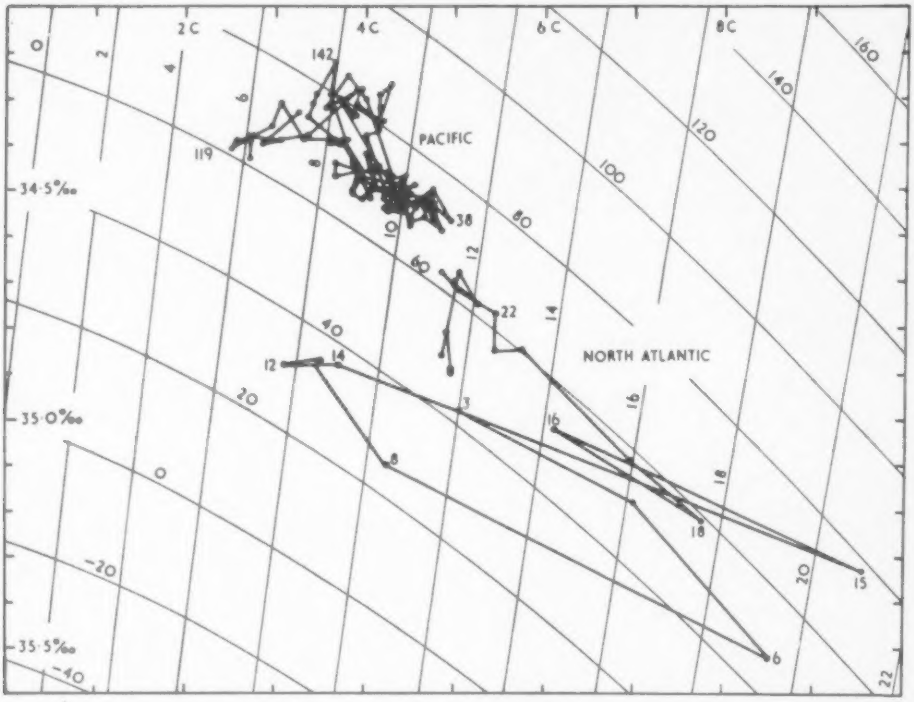

Fig. 3. Temperature-salinity diagram for 1,000 db. All *Carnegie* stations reaching 1,000 db are represented by the dots consecutively connected; some are labelled with station numbers. The diagonal curves represent thermosteric anomaly. The nearly vertical lines represent the pressure terms of specific-volume anomaly at 1,000 db. Both families are labelled in centilitres per ton.

Another way of assessing the pressure terms is by study of Fig. 3, a temperature-salinity diagram for 1,000 db at 154 *Carnegie* stations. Thermosteric anomaly and the pressure terms are shown by the two families of lines. For the Pacific stations the range in pressure terms is seen to be only 6 cl/ton (centilitres per ton), which for a 500-db layer amounts to 3 cm in thickness, and the change between adjacent stations is at most about 1 cl/ton. The Atlantic stations cover a greater area on the diagram, which thus reflects greater baroclinity at 1,000 db in the Atlantic than the Pacific.

The conclusion is reached that for hydrostatic computation limited to the upper 500 db or 1,000 db, especially in the Pacific Ocean, if extreme precision is not required and if significant convenience is gained, the pressure terms may be neglected; in other words, the thermosteric anomaly δ_T may be used in place of the complete specific-volume anomaly δ.

THERMOSTERIC ANOMALY RECOMMENDED

Oceanographers have fallen into the cumbersome habit of using both density and specific volume, the first as sigma-t and the second as anomaly of specific volume.* It would be better in all routine work to adhere to one or the other. The question is which to choose.

Sigma-t (σ_t) is defined as the excess above one gram per millilitre that the density would attain if the water were changed isothermally to a standard pressure of one atmosphere. Density ρ and specific volume bear the relation $\alpha\rho = 1$. Hence, thermosteric anomaly and sigma-t bear the relation

$$(\alpha_{35,0,0} + \delta_T)(1 \text{ g ml}^{-1} + \sigma_t) = 1, \qquad \alpha_{35,0,0} = 0{\cdot}972643 \text{ ml/g}$$

Sigma-t is commonly used as a quasi-conservative or identifying property of water type. For any such purpose, including isentropic analysis, the use of thermosteric anomaly is equally suitable. Sigma-t has the advantage that it has become established in habit. Thermosteric anomaly has the convenience that it is expressed, for most ocean water, in a number of two or three digits only, whereas the corresponding number in sigma-t has four digits.

The use to which specific-volume anomaly is commonly put is in hydrostatic computation by the method indicated in equation (1). Hydrostatic computation can also be carried out by integrating the density anomaly ϵ,

$$(p_1 - p_2)_a = \int_{\phi_1}^{\phi_2} \epsilon \, d\phi. \tag{3}$$

Both methods are discussed by BJERKNES (1910). There are some reasons to prefer the method of equation (1). One reason is that this method has become customary. This method gives the geopotential difference between chosen isobaric surfaces. The geostrophic equation for isobaric surfaces is the simplest because it does not involve density, which appears in the geostrophic equation for a level surface. For this reason, isobaric surfaces have been adopted in meteorology as the basis for upper-air analysis. Furthermore, if pressure is directly observed, the integration in (1) involves observed quantities and yields geopotential difference as a result. If depth rather than pressure is observed, the integration (1) is more convenient than (3), because the number of metres of depth equals the number of decibars of pressure within one per cent in the upper layers, whereas the number of metres of depth differs from the number of 10^5 ergs per gram of geopotential difference by about two per cent.

The conclusion is reached that it would be better in all routine work to adhere to specific volume. It is desirable, therefore, to replace the use of sigma-t with the use of thermosteric anomaly. The most important specific-volume quantity to tabulate with serial observations, in our opinion, is thermosteric anomaly. If specific-volume anomaly is to be tabulated along with thermosteric anomaly, the computation will be easier than has been the computation of both sigma-t and specific-volume anomaly.

Convenient tables exist for the calculation of thermosteric anomaly. Besides the Hydrographic Tables of BJERKNES (1910), there is the convenient new Table V of LAFOND (1951) for the salinity range from 21 to 37 per mille and temperature range from -2 C to 30 C.

* Another such habit is the use of both salinity and chlorinity.

Another method is to read thermosteric anomaly from a temperature-salinity diagram bearing the isopleths, as in Fig. 3. Furthermore, the pressure terms, and hence the complete anomaly of specific volume, can be obtained from such a temperature-salinity diagram. This method is feasible because the pressure terms are nearly linear with pressure. (As may be seen from the tables of BJERKNES or SVERDRUP, the relation is linear, for practical purposes, from 0 db to 2,000 db or deeper.) It is convenient to have the pressure terms for 1,000 db drawn on the diagram, as in Fig. 3, so that the value from the diagram needs merely to be multiplied with the ratio of the pressure to 1,000 db.

ANALYSIS OF SECTIONS

A recent paper by one of us (MONTGOMERY, 1954) describes a unified method of analyzing a section of serial observations, the aim being to achieve consistency in the description of the different fields (temperature, salinity, sigma-*t*, oxygen . . .). Sigma-*t* was chosen as the reference field. As concluded above, it now appears desirable to replace sigma-*t* with thermosteric anomaly.

In the paper mentioned, no attempt was made to incorporate hydrostatic computation into the analysis and to represent the geostrophic flow through the section. The field of thermosteric anomaly that results from this analysis is based on a systematic study of all pertinent data and is more reliable than a simple interpolation of water-bottle data for each station independently. This field should therefore form the basis for hydrostatic computation along the section.

By adding the pressure terms, the field of thermosteric anomaly can be converted to the field of specific-volume anomaly. It has been seen, however, that the pressure terms are unimportant for some problems. For these problems the field of thermosteric anomaly may be used directly in the hydrostatic equation (1) in place of specific-volume anomaly.

For isopleths of either specific-volume anomaly or thermosteric anomaly the word *isanostere* is proposed.

The starting point is the vertical section showing isanosteres on coordinates of horizontal distance (x) and pressure (p). There are two ways to proceed with the hydrostatic computation. The first method is to compute the anomaly of geopotential difference between chosen isobaric surfaces by summing the pressures of isanosteres at each chosen vertical line. The second, introduced by WERENSKIOLD (1935, 1937), is to compute the relative slope of chosen isobaric surfaces by summing the slopes of isanosteres at each chosen vertical. The first is more direct if the position of the sea surface relative to a chosen isobaric surface is desired; the second is more direct if the slope of an isobaric surface is desired for use in the geostrophic equation. The two methods are discussed in turn. Note that in either of these graphical methods the computation can be made for any verticals, which need not coincide with stations.

For the first method, the variable of integration in (1) is changed from pressure to anomaly of specific volume,

$$(\phi_2 - \phi_1)_a = p_1\,\delta_1 - p_2\,\delta_2 + \int_{\delta_1}^{\delta_2} p\,d\delta. \tag{4}$$

If the isanosteres are drawn for a uniform, small increment $\Delta\delta$, the integral in (4) can be evaluated for any vertical on the section by summing the pressures of the

isanosteres directly from the section and multiplying by the increment $\Delta\delta$.

For WERENSKIOLD's method, the integral in (1) is differentiated with respect to x, the distance along the section,

$$\frac{d}{dx}\int_{p_1}^{p_2}\delta\,dp = \int_{p_1}^{p_2}\left(\frac{d\delta}{dx}\right)_p dp = \int_{\delta_1}^{\delta_2}\left(\frac{d\delta}{dx}\right)_p\left(\frac{dp}{d\delta}\right)_x d\delta = -\int_{\delta_1}^{\delta_2}\left(\frac{dp}{dx}\right)_\delta d\delta,$$

the last step being a consequence of the relation between thiee variables

$$\left(\frac{d\delta}{dx}\right)_p\left(\frac{dx}{dp}\right)_\delta\left(\frac{dp}{d\delta}\right)_x = -1.$$

Hence,

$$\frac{d}{dx}(\phi_2 - \phi_1)_a = \int_{\delta_1}^{\delta_2}\left(\frac{dp}{dx}\right)_\delta d\delta. \tag{5}$$

(This result could be obtained by differentiating (4)). If the isanosteres are drawn for a uniform, small increment $\Delta\delta$, the integral in (5) can be evaluated for any vertical by summing the slopes of the isanosteres and multiplying with the increment $\Delta\delta$.

Let v_n be the geostrophic-current component normal to the section, positive v_n being directed contra solem from positive x. The geostrophic equation is

$$f(v_{n2} - v_{n1}) = d(\phi_2 - \phi_1)_a/dx,$$

where $f = 2\omega \sin\phi$ is the Coriolis parameter, ω being the angular speed of the earth's rotation and ϕ being latitude. The quantity on the right results directly from (5) or indirectly from (4).

In conclusion, the method of analysis previously described should be modified by replacing sigma-t with thermosteric anomaly. The field of thermosteric anomaly can be converted to the field of specific-volume anomaly by adding the pressure terms, but the method is most convenient when the pressure terms may be neglected completely. As part of the analysis, hydrostatic computation can be carried out graphically by one of the methods just described.

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Brown University, Providence 12, *Rhode Island.*

(R. B. MONTGOMERY, now at Chesapeake Bay Institute, The Johns Hopkins University, Baltimore 18, Maryland).
(WARREN S. WOOSTER, of Scripps Institution of Oceanography, University of California, La Jolla, California, temporarily at Brown University.)

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Further measurements of the sound scattering properties of several marine organisms

PAUL FERRIS SMITH

Summary—Investigations of underwater sound scattering by marine organisms have been continued under more favourable operating conditions and using improved instrumentation. The results corroborate and extend those obtained and reported earlier that shrimp as well as fish and squid are effective sound scatterers. The present data also include measurements of scattering by as few as one large shrimp. The results of fish, squid and large shrimp are analyzed to give the effective scattering area of each over a frequency range of from 8 Kc. to 30 Kc. Assuming an idealized layer an estimate is made using these values of the number of scatterers of each type necessary to account for the volume reverberation reported for the deep scattering layer.

INTRODUCTION

Using a modified form of the experimental technique developed and reported earlier (SMITH, 1951) for quantitive echo ranging over short distances at various frequencies, a series of sound scattering measurements have been made on squid (*Loligo pealei*), scup (*Stenotomus versicolor*), sea bass (*Centropristes striatus*), and shrimp (*Palaemonetes vulgaris* and *Penaeus setiferus*). The purpose of these measurements was to determine the dependence of acoustic cross section of possible marine scatterers upon frequency of the sound and the size and structure of the scatterer. This information is required in evaluating the several biological hypotheses (CHAPMAN, 1947 ; HERSEY and MOORE, 1948 ; LYMAN, 1948 ; MOORE, 1948 ; 1950) for the origin of the deep scattering layer and will also provide some quantitive information to assist the development of acoustic ranging methods for fish detection. This report describes the instrumentation, method of observation and results obtained.

EXPERIMENTAL TECHNIQUE

All operations were conducted aboard a 35 × 15 foot raft moored in water 25 feet deep on a fresh-water pond (Flax Pond, East Falmouth, Massachusetts) one-third mile in diameter. The electronic equipment, power for which was supplied by a gasoline generator on shore, was mounted in a 15 × 15 foot house at one end of the raft and the underwater equipment was lowered through a central opening. It was found necessary to surround the raft with a surface-to-bottom net (a used mackeral seine having $\frac{3}{4}''$ mesh was used) and fire electric blasting caps to rid the operating region of unwanted eels and other fish. Attempts to overcome this problem by contamination of the water in the vicinity with sodium hypochlorite or rotenone did not work.

Equipment and Measurements

The echo ranging equipment (Fig. 1) produced one to one-half millisecond pulses of sound over a frequency range from 8 to 31 kilocycles at a repetition rate of about one every half second and received either the direct or backward scattered sound. Additional equipment (Model OCP-1 Sonar Monitor with a CAEK-51112 Trans-

ducer) was available to make receiving response calibrations of the transducers. These calibration curves, which do not vary more than $\pm$ 1·5 db. from run to run, and the voltage comparison method of calibration were used to determine the intensity of the outgoing pulse and the backward scattered sound by visual observation of an oscilloscope whose sweep was triggered by the transmitted signal.

Experimental Procedure

All measurements were made at a depth of about 3 meters at which was located, on the end of a 1″ pipe, the QBE (transmitting) and the QBG (echo-receiving) trans-

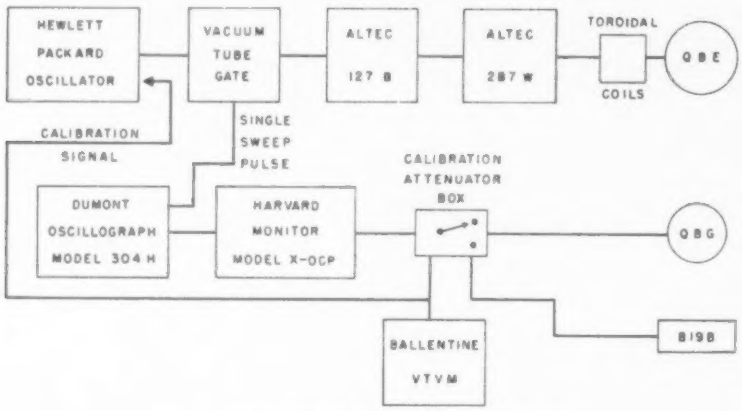

Fig. 1. Echo ranging Equipment block diagram.

ducers. This rig could be rotated so as to echo from a scatterer at this same depth and at a range from one to two meters. Due to the construction of the raft it was found most desirable to operate at a range of 1 m. After finding that the positioning of the echoer was very critical at this close range, a series of echo directivity patterns were taken to make certain all scatterers used were placed within the volume of water for which no directivity correction was necessary. At this 1 m range, an area 17 $\times$ 21 cm centered normal to the horizontal axis of the sound path defined the limit in which the echo had not fallen off more than 2 db with respect to that from an echoer directly on the axis. It was decided that, with a calibration reproducibility of $\pm$ 1·5 db, no directivity correction would be required for scatterers restricted to this plane. Care was taken not to use scatterers or arrays of scatterers that extended beyond these dimensions. To assure centering of any scatterer within this area, the depth of the scatterer and

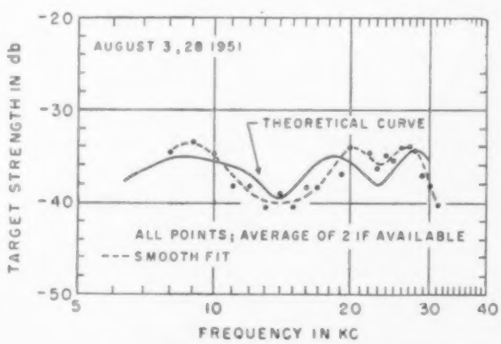

Fig. 2. Target strength of brass sphere.

the orientation of the QBE-QBG rig were varied until the maximum echo was received. The outgoing pulse was measured by placing the B-19-B hydrophone at this same point by the same method.

The method of supporting the scatterers might well affect the results ; it was carefully investigated at the outset. In every case, the scatterer under observation was supported by one or more vertical 0·014″ diameter stainless steel wires 6 m long weighted at the lower end. Scattering measurements over the frequency range 8 to 30 Kc. were made on all of these bare supporting wires to determine their con-

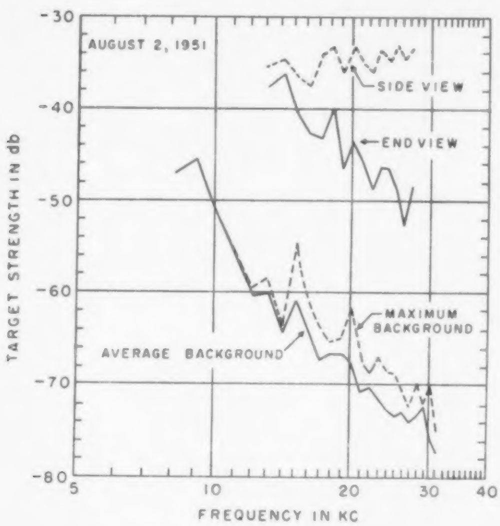

Fig. 3. Target strength of sea bass.

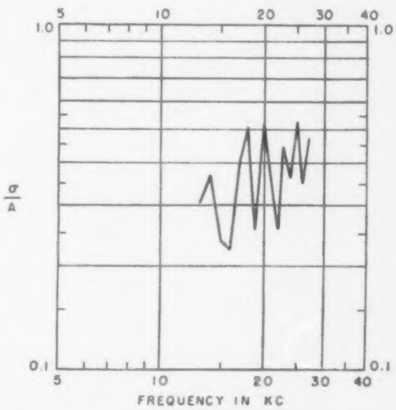

Fig. 4. Variation of effective target area with frequency-for Sea bass.

tribution to the total scattered sound when the scatterer was present. This is called the background scattering. The background target strengths measured for one, two, ten, twenty and fifty of the 0·014″ diameter stainless steel supporting wires were not significantly different. This was due in part to their failure to show above the scattering observed when no wires were present and to their rather large variability ($\pm$ 4 db.) from one frequency setting to the next. In consideration of this, a composite average of all these background measurements was made ; this is plotted on all figures showing background target strength. With this average curve is plotted a dotted line connecting the maximum background scattering values obtained at each frequency (see Figs. 3, 5, 7, 8, and 10).

To test reliability of the experimental procedure, the scattering by a 6·17 cm diameter solid brass sphere was measured, since its scattering can be computed from theory. A comparison of theory and experiment shows agreement quite satisfactory for the present purposes (Fig. 2), the experimental values lying within 2 db. or less of the theoretical curve.

To elimate air bubbles on or in the scatterers, all scatterers were placed in water in a vacuum dessicator and held at a pressure of about 1 cm. of mercury for at least one hour and then attached to the supporting wires without exposure to air. To further safeguard against the formation of air bubbles of films whenever a hydro-

phone or metal echoer was lowered into water, they were washed with a detergent and detergent was sprinkled on the surface of the water through which they passed. Despite the precautions to eliminate air bubbles there is still the possibility that some were present and undetected. A line is therefore drawn on Fig. 8, showing the calculated value one resonant bubble would give at each frequency used. In only one instance (the maximum value at 15 Kc.) does evidence of bubble contamination appear in the background scattering. Results for the specimens (except Fig. 8) would have required a very large number of bubbles conveniently resonant at many frequencies.

The actual area of the scatterer normal to the sound beam was determined by tracing around the scatterer, placed on a piece of paper as it had faced the transducers, and measuring the resulting area with a planimeter.

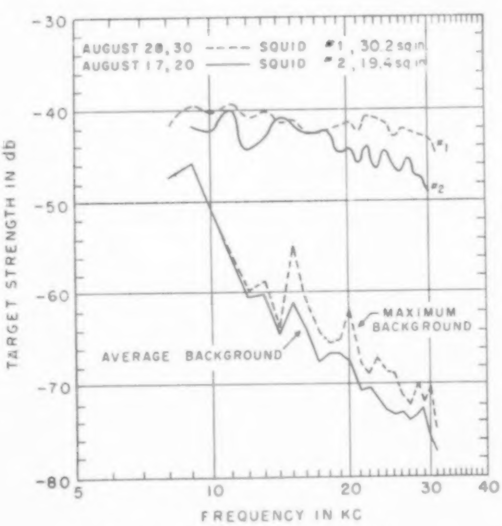

Fig. 5. Target strength of squid.

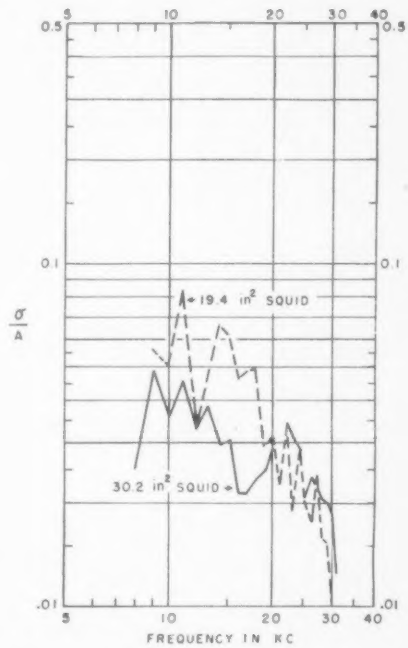

Fig. 6. Variation of effective target area with frequency-for two individual squid.

Precision and Reliability

The purpose of the measurements reported herein was, in part, to repeat, extend, and improve similar measurements made in 1950 and reported earlier (SMITH, 1951). It is felt that this aim has been accomplished. The scattering values obtained from the brass sphere were both more reproducible (less than 1 db variation as compared with 2 db.) and fitted more nearly the calculated values (Fig. 3) than the 1950 data ; The measurements then are probably precise to within 1 to 2 db. since the results do not depend on calibrations other than those that were part of the observations. The rapid pulse repetition rate and the continuous visual observation of the oscillo-

scope trace placed the observer in more constant communication with the experimental conditions than was possible when using the previous photographic method of recording. In fact, it was by thus observing the echo on the oscilloscope that the definite presence of unwanted fish was detected. These fish were later observed through a water glass from the surface. Other factors that improved the results indirectly by contributing to the ease of operation were the prevailing quiet water conditions on the pond and the simplicity of handing gear on the new raft.

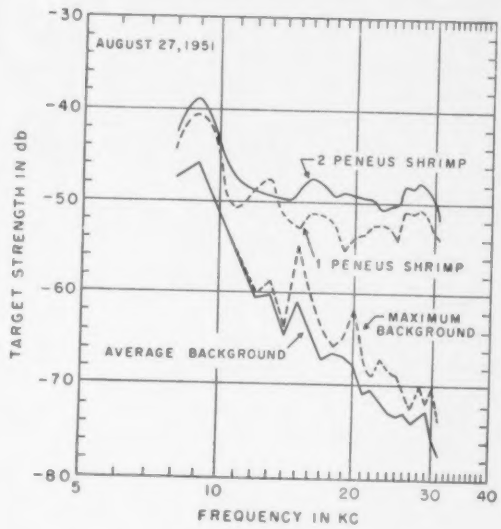

Fig. 7. Target strength of penaeid shrimp.

ANALYSIS OF DATA

The ratio of the back scattered sound intensity 1 yard from a scatterer to the sound intensity incident upon it, defined as its Target Strength, was determined for each of the above marine organisms, for the brass sphere and for the bare frames at each kilocycle from 8 to 31 (Figs. 2, 3, 5, 7, 8, 10, and 11).

Since the above definition of target strength is equivalent to

$$T = 10 \operatorname{Log} \frac{\sigma}{7\pi}$$

where σ is the effective target area, the value of σ for each scatterer is computed, and the ratio σ/A is plotted against frequency (Figs. 4, 6, 9 and 12). A is the actual area of the scatterer normal to the incident sound.

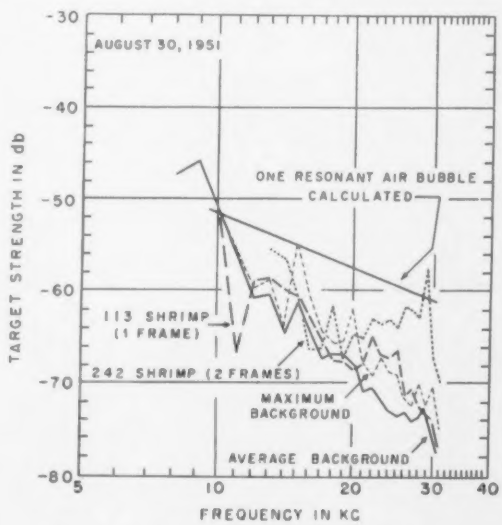

Fig. 8. Target strength of palaemonid shrimp.

To make possible a comparison of the present results with field observations others have made on the deep scattering layer, the quantity scattering cross section per unit volume, called volume scattering coefficient m, is employed. By definition, this may be written

$$m = N\sigma$$

where N is the number of scatterers per unit volume and σ is the effective scattering

cross section of each scatterer. Using for convenience the average σ obtained for each scatterer over the range 15 to 25 Kc and reported volume scattering coefficients from the literature, the corresponding number of each type of scatterer per unit volume is computed. These results (Table I) depend upon the value of m for the deep scattering layer. Since the reported volume scattering coefficients (BAZTLER and WESTERFIELD, 1953) differ considerably, two values near the extremes were chosen as noted in the table.

Table I. Scattering cross sections and corresponding population densities to give reverberation levels observed at sea for the various scatterers measured.

Type of Scatterer	*Average σ, yd²* (*15 to 25 Kc*)	*Scatterers/yd³ to give* m_1 (1)	m_2 (1)
1 Shrimp (*Palaemonetes*)[2]	$2{\cdot}32 \times 10^{-8}$ (3)	13	216
1 Shrimp (*Penaeus*)	$6{\cdot}56 \times 10^{-5}$	$4{\cdot}6 \times 10^{-3}$	$7{\cdot}6 \times 10^{-2}$
Scup	$3{\cdot}8 \times 10^{-4}$	$7{\cdot}9 \times 10^{-4}$	$1{\cdot}3 \times 10^{-2}$
Squid #2	$5{\cdot}33 \times 10^{-4}$	$5{\cdot}6 \times 10^{-4}$	$9{\cdot}4 \times 10^{-3}$
Squid #1	$8{\cdot}29 \times 10^{-4}$	$3{\cdot}6 \times 10^{-4}$	$6{\cdot}0 \times 10^{-3}$
Sea Bass	$4{\cdot}4 \times 10^{-3}$	$6{\cdot}8 \times 10^{-5}$	$1{\cdot}1 \times 10^{-3}$

1. $m_1 = 3 \times 10^{-7}$ yd^{-1}, $m_2 = {\cdot}5 \times 10^{-6}$ yd^{-1}.
2. Obtained from an average σ of $5{\cdot}34 \times 10^{-6}$ yd² for two groups of 242 and 220 Palaemonetes.
3. This average is for 20 to 30 Kc.

RESULTS

Results and comparisons for the several animal scatterers are given below. All specimens, unless otherwise noted, were alive when taken to the raft and killed shortly before the acoustic measurements were taken.

Sea Bass. The target strength values obtained for one sea bass are shown in Fig. 3. During preliminary observations it was observed that orientation of this scatterer greatly influenced the echo level. Therefore, two runs are shown ; one with the sea bass held broadside to the sound axis, and one with it held parallel to this axis. The ratio of the effective target area (broadside) to actual area is shown in Fig. 4 for each frequency measured.

The two sea bass target strength curves in Fig. 4 approximately span the 1950 data. It is interpreted, therefore, that these two sets of measurements check one another (both fish used were full grown) but that in 1950 the effect of orientation was not investigated.

The high value of effective target area for this scatterer (average $\sigma/A = 0{\cdot}35$) when compared with the squid (average $\sigma = 0{\cdot}03$) suggests that scatterers having heavily calcified endoskeletons with calcified scales (fish) are much more efficient reflectors than those having no scales and noncalcified endoskelton (like squid). While that may be the case, the fact that the value for the effective target area of the scup lies in between the above two (average $\sigma = 0{\cdot}09$) neither wholly corroborates nor invalidates this conclusion.

While it is not believed they have influenced the results, two facts must be noted that may have caused the sea bass values to be high. No net or blasting caps were used to eliminate unwanted fish during this series and the actual area of the sea

bass was estimated from the measurement of its length and width. When spurious fish were detected (and they were noted the first day squid were used), the evidence of their presence was rather dramatic on the oscilloscope. It therefore seems highly unlikely that their presence went unnoticed during the earlier sea bass run. The area estimate can be assumed to be off no more than 25% and this would not bring the

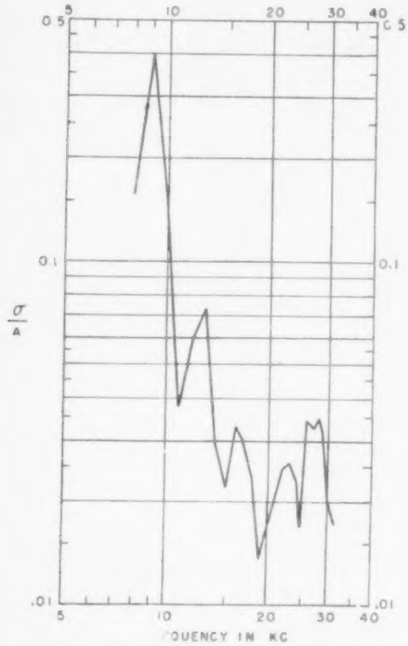

Fig. 9 Variation of effective target area with frequency for one penaeid shrimp.

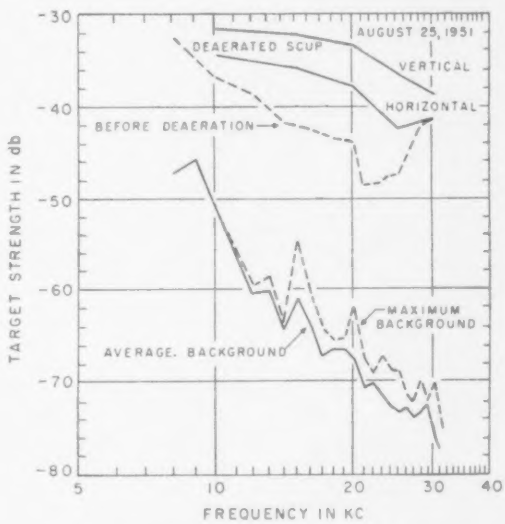

Fig. 10. Target strength of scup. #1.

σ/A values for the scup and sea bass together. Thus, these two factors do not appear to warrant discarding the sea bass data. The difference in the two effective target areas is, therefore, ascribed to physical differences in the fish, but this cannot be verified without further data.

Squid. Both target strength values (Fig. 5) and the ratio of effective target area to actual vs frequency (Fig. 6) are plotted for two squid having areas of 30·2 and 19·4 in.^{2} respectively. No other comparison will be made between the 1950 results and these because of the unreliability reported for the former data, except to observe that the present values lie between the two earlier sets.

Shrimp. Two readily-available kinds of shrimp, *Penaeus* (these were preserved specimens) and *Palaemonetes*, were used to approximate respectively the red prawns and euphausids that are caught at the depths of the scattering layers. In Figs. 7, 8 and 9 are presented the results of these observations.

Scup. Figs. 10 and 11 give the target strength results obtained from two different scup. These values provide an excellent illustration of the wide range in the intensity of scattering by a single marine target depending both upon its orientation with the sound axis and upon frequency.

In Fig. 10 the dashed curve represents the target strength values for the first scup before deaeration and when supported approximately parallel to the sound axis. This simulates the natural aspect for midwater reverberation received at the surface. The two solid curves connect the values obtained after deaeration and with the scup supported carefully parallel and then normal to the sound axis. The apparent increase after deaeration is ascribed solely to orientation as illustrated by Fig. 11 which gives

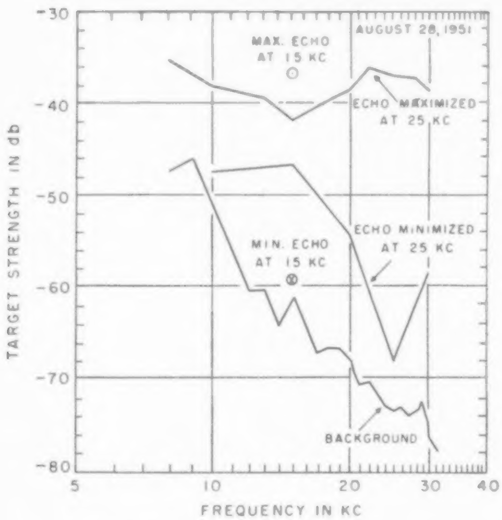

Fig. 11. Target strength of scup. #2.

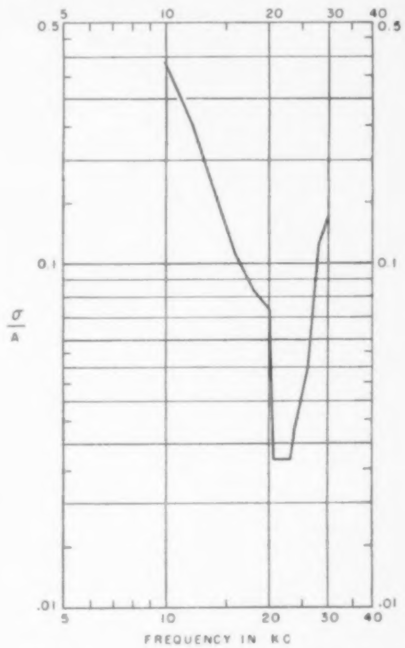

Fig. 12. Variation of effective target area with frequency-for scup (average #1).

target strengths for the second scup. Due to equipment failure this scup was not deaerated. The large dependence (over 30 db.) of scattering level on orientation and frequency is clearly evident here. The upper curve was obtained after orienting the scup to give a maximum at 25 Kc. The two points at 15 Kc. represent the maximum and minimum at this frequency. Fig. 12 gives σ/A vs frequency for the average of the two solid curves of Fig. 10. Similar curves for scup #2 have not been computed.

DISCUSSION

Table 1 gives the population densities required to account for representative large and small volume scattering coefficients (University of California, Division of War Research, 1946). Considering the restricting assumptions necessary to compute these values of population densities and the inability at present to compare these with absolute population densities, these values are presented with only the comment that they do not conflict with present biological knowledge, except that a population density of 216 yd^{-3} for the palaemonid shrimp is regarded as improbably high.

There is no truly satisfactory way of assessing the physical data on sound scattering since the shape of the specimens precludes any computations of target strength.

Approximately the correct scattering was observed for the brass sphere, and though there may have been gas bubbles present in some of the measurements they have not significantly affected the measurements reported. The effective target areas all vary somewhat irregularly with frequency, a result which fits qualitatively with the fact that all dimensions of the specimens are comparable to the wave lengths of the sound (ANDERSON, 1950). In no instance have the results followed the Rayleigh scattering law (STRUTT, 1945) which applies when the dimensions of the scatterer are small compared with the wave length and would appear in Figs. 3, 5, 7, 8, 10 and 11 as a 12 db. per octave *increase* in target strength with frequency (Note : scattered intensity varies directly as the fourth power of the frequency). Indeed, target strengths of the squid, penaeid shrimp and scup show a general trend inverse to frequency ; higher values of scattering cross section may well be found at lower frequencies. Work is therefore now in progress to extend these measurements below 8 Kc. with the aim of extending them well into the Rayleigh region.

The results for the palemonid shrimp are not satisfactory, the signal-to-background-reverberation being entirely too low. However, these measurements serve to set an upper limit for scattering cross section for these shrimp.

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Survey of a newly discovered feature (*Genista Bank*) off the Arabian Coast

COMMANDER G. P. D. HALL, D.S.C., R.N.

WHILE employed on convoy escort duty in 1944, H.M.S. *Genista* reported the existence of a 40-fathom bank some 13 miles south-west of *Ras Sajir*, on the south coast of Arabia. Fig. 1, taken from Admiralty Chart No. 3784, shows the position of the bank in relation to the land. At first glance the presence of a Sea-mount is suggested, though for lack of precise knowledge of its morphology it could, until now, be referred to only as a Sea-high.

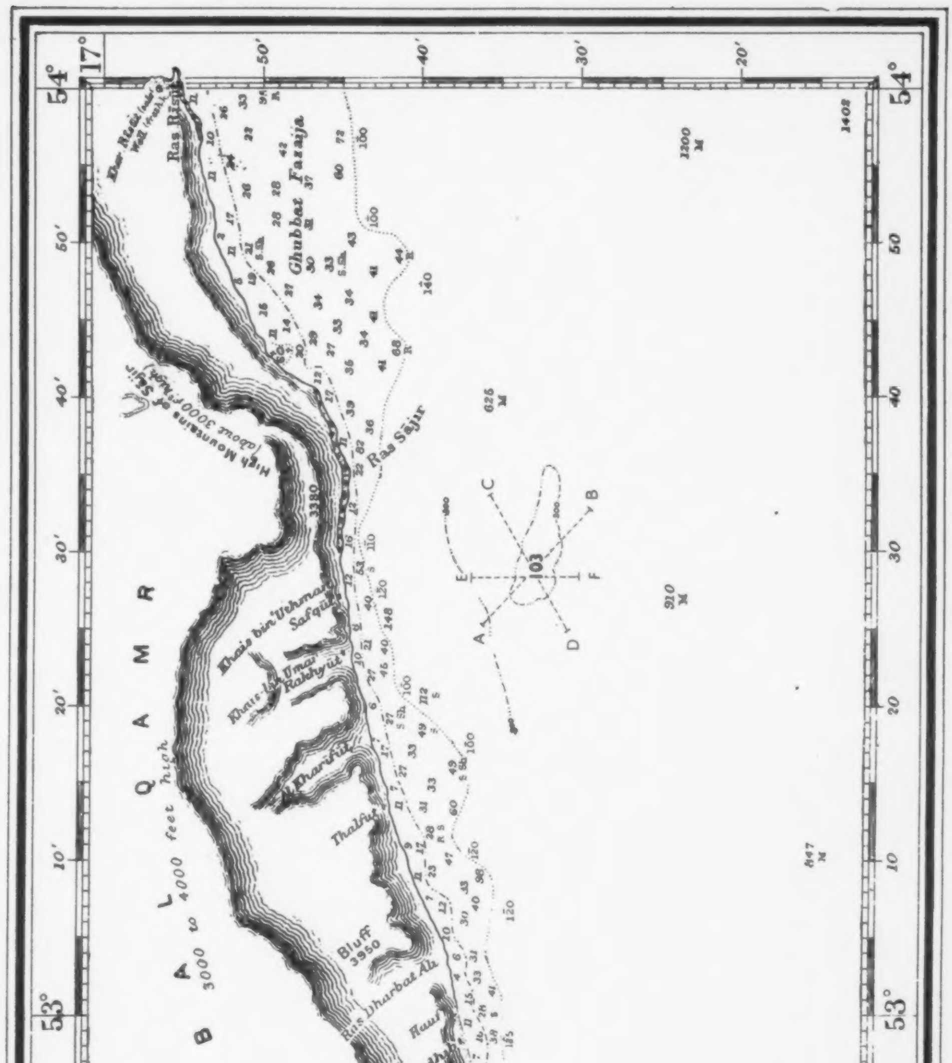
The passage of one of H.M. Surveying Ships to the Persian Gulf, however, recently afforded the Admiralty an opportunity of carrying out a hydrographic survey of this feature. The task was performed by H.M.S. *Owen* (Lieut. Cmdr. J. T. K. PAISLEY, R.N.) in the space of two days, in December, 1953.

The bank was found without difficulty, and a floating radar beacon was anchored approximately on its summit, in a depth of 106 fathoms. The position of the beacon was determined by celestial observations and taut wire measurements from inshore fixes. Lines of soundings were then run as shown in Fig. 3, positions being fixed by radar ranges and gyro-compass bearings of the beacon. Soundings are in fathoms, reduced approximately to the level of low water springs, and corrected for the speed of sound in sea-water, from MATTHEWS (1939) Tables.

The survey reveals a well-defined feature, consisting of a roughly ellipitical bank with a gradual slope to the eastward and with comparatively steep southern and western faces. It rises from depths of 400-500 fathoms in the north, to a least depth of 103 fathoms at the summit, and falls away to some 900 fathoms in the south.

The 40-fathom depth reported by H.M.S. *Genista* is virtually disproved, and it seems probable that the echoes obtained on that occasion resulted from fish, eddies, or other aqueous phenomena, a number of false echoes also being observed and remarked on by H.M.S. *Owen*.

To consider further the nature of the feature that has now been revealed, and to apply the appropriate terminology, it is necessary to refer to Fig. 2, which shows approximate profiles along the lines *AB*, *CD* and *EF*. Unfortunately, there is insufficient evidence on which to extend the profiles inshore to the 100-fathom line, and in consequence the precise nature of the connection with the continental shelf is unknown. If it is assumed, however, that the sea-bed slopes down at a fairly uniform gradient from the 100-fathom line to *A* and *E*, the feature would appear to be a comparatively isolated extension of the continental shelf, and therefore not, strictly speaking, an oceanic feature. It cannot be classed as a Sea-Knoll, within the definition of which it might otherwise have fallen, and the only appropriate term for its description appears to be a bank. No suitable geographical name suggests



Reproduction of portion of Admiralty Chart 3784.

Fig. 1.

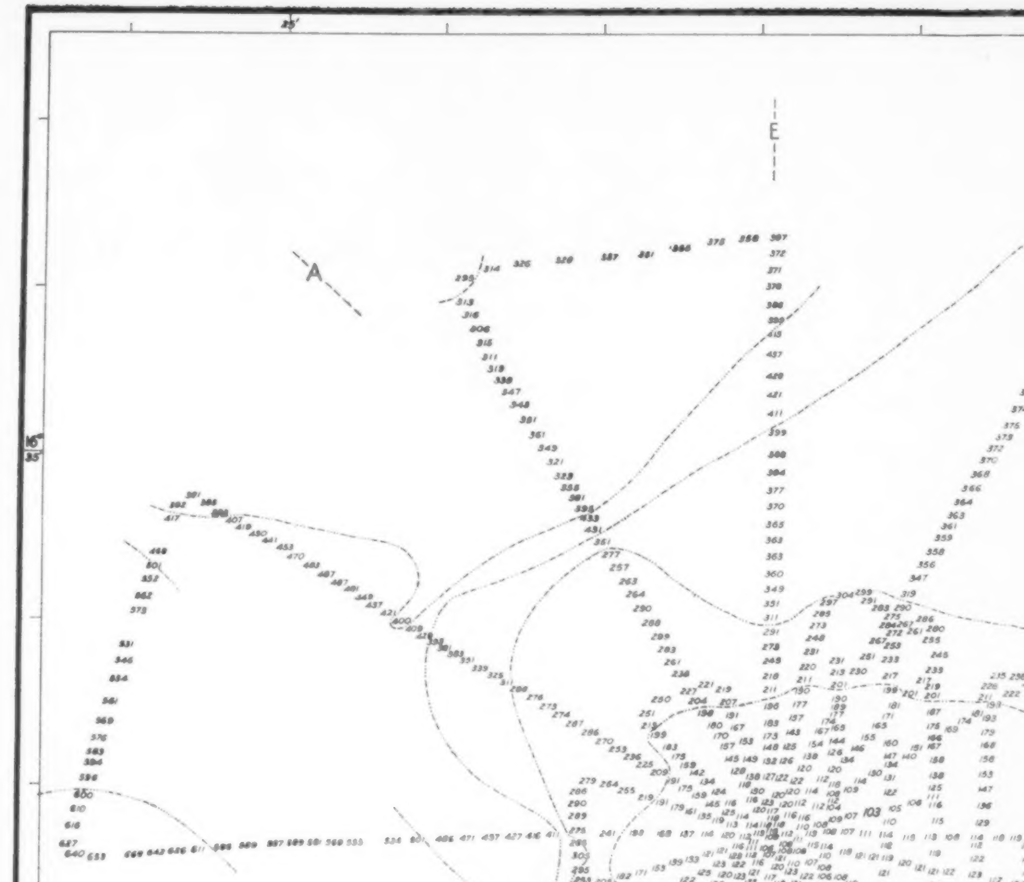
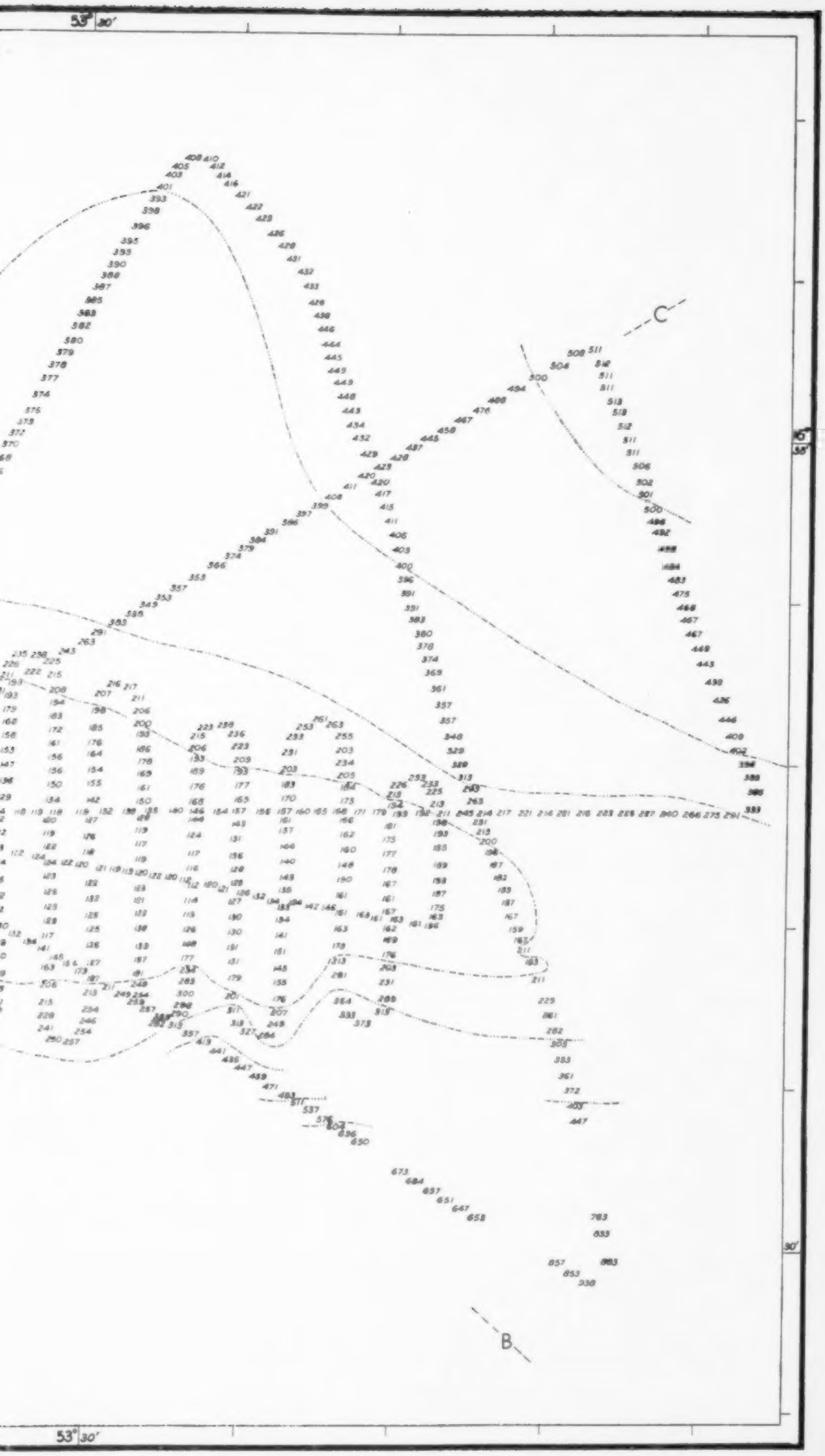


Fig. 3.


53° 30'
C
B
30'
53° 30'

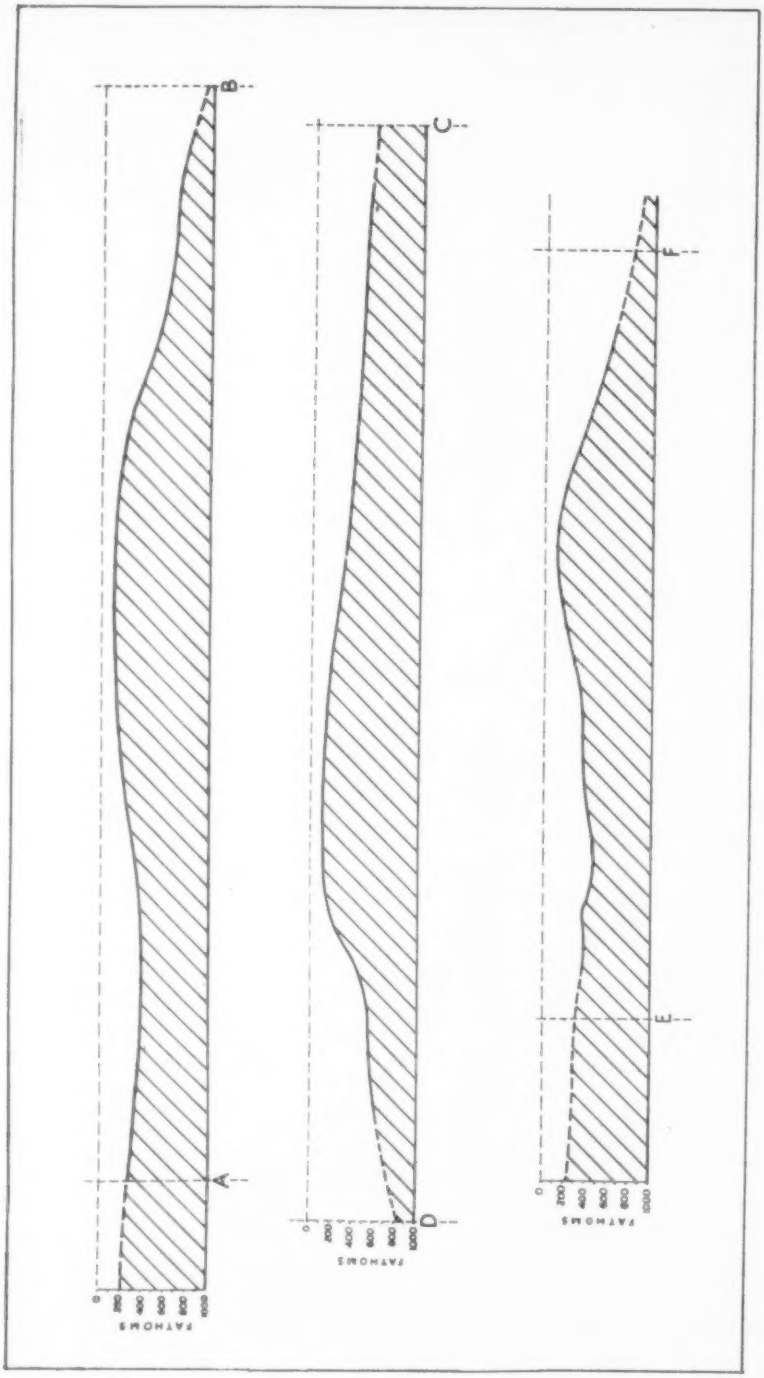


Fig. 2.

itself, and it is being proposed through the appropriate channels that the feature should henceforward be known as the " Genista Bank."

Published by permission of the Admiralty.

British Admiralty Hydrographic Department.

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An oceanographic organization for the Indo-Pacific region

The study of the oceans has for many years been recognized as a field in which international collaboration is most important. The national efforts can only become entirely efficient if they can be correlated by some permanent international body, responsible for meetings of experts at regular intervals, publications, etc.

This was the idea in the mind of Otto Pettersson, the Swedish oceanographer, when he first took the initiative for such collaboration, which led to the first conference in Stockholm in 1899 concerning the creation of a permanent international council for the problems of the seas bordering the N.W. European countries. The final goal was to promote the fisheries, but it is gratifying to see that most of the men meeting were those we today consider founders of Oceanology. Besides Otto Pettersson, we find John Murray, D'Arcy Thompson, V. Hensen, O. Krümmel, Martin Knudsen, C. G. Johs. Petersen, Johan Hjort and Fridtjof Nansen at the meeting, all enthusiastic about the plan.

Another meeting was held in Oslo, 1901, and finally a definite constitution was decided at Copenhagen in 1902. The name given to this organisation was the *Conseil Permanent International pour l'Exploration de la Mer* and the adjective *permanent* carries a happy witness about the optimism behind it ; and *permanent* it has since been, still very much alive despite of two world wars. From concentrating on the North Sea region in the beginning it now covers the waters as remote as Greenland and Spitzbergen southwards to the Equator.

The urgent need for developing the fisheries in the Indo-Pacific has led to the creation of the Indo-Pacific Fisheries Council (I.P.F.C.), which naturally concentrated on marine food resources.

In October, 1952, the I.P.F.C., at its fourth meeting held in Quezon City, Philippines, adopted a report and a Resolution on International Oceanographic Requirements, which were transmitted by F.A.O. to the Director General of UNESCO. The resolution emphasized that UNESCO has a rôle in the development of fundamental knowledge concerning oceanography and FAO has an interest in applying such fundamental knowledge to particular fishery problems.

The holding in Manila, in November 1953, of the Eighth Pacific Science Congress offered an excellent opportunity to discuss the question. Invitations were therefore issued jointly by UNESCO and FAO to a number of congress participants to meet in Manila a few days before the beginning of the congress to discuss the needs and possibilities of establishing an oceanographic organization in the Indo-Pacific region.

The persons acting as consultants to UNESCO and FAO were Dr. J. D. F. Hardenberg, Djakarta ; Professor A. C. Hardy, Oxford ; Professor K. Hidaka, Tokyo ; Dr. B. Indrambarya, Bangkok ; Professor Th. Monod, Dakar ; Professor T. Okada, Tokyo ; Dr. N. K. Panikkar, Mandapan ; Professor Hans Pettersson, Göteborg ; Dr. D. J. Rochford, Cronulla ; Professor R. Seréne, Nhatrang ; Professor Thomas G. Thompson, Seattle ; Mr. A. Tubb, Hong Kong ; Dr. J. P. Tully, Nanaimo ; Dr. D. V. Villadolid, Manila, and Dr. A. Fr. Bruun, Copenhagen.

FAO was represented by Dr. Cecil Miles, Bangkok, who was elected *rapporteur*, and UNESCO by its Director of the Department of Natural Sciences, Professor P. Auger, who was elected chairman of the meeting ; furthermore Dr. A. Wolsky and Mr. J. Smid of the UNESCO offices in Djakarta and Manila participated, and as observers Dr. D. L. Hudson, Pacific Science Association, and Mr. E. H. Dahlgren and Mr. M. J. Lobell, Foreign Operations Administration of U.S.A. from the offices in Djakarta and Bangkok. (Detailed minutes of the four meetings can be obtained from the Secretariat of UNESCO, Department of Natural Sciences, UNESCO House, 19 Avenue Kléber, Paris 16^e.)

At the end of its proceedings, the Committee of Consultants unanimously adopted a resolution, firstly stating that there was an urgent need for the establishment of an organization in the Indo-Pacific region for fundamental oceanographic research. The term Indo-Pacific region was for the present purposes restricted to include the water masses between the tropic of Capricorn and 35°N. latitude and between the east coast of Africa and 160°E. longitude. The object of the organization should be to contribute to the advancement of scientific knowledge of the oceans, in the fields of physics, chemistry, geology, meteorology and biology with the principal aim of providing the basic information necessary for the rational exploitation of the resources of the sea.

Only a few points of the principal functions may be mentioned here, simply because, as they were defined, all of them were what probably most oceanologist would agree to for starting such an organization. As to documentation a census of existing scientific institutions, projects, etc. concerned with oceanography in the region, and a compilation of a record of oceanographic data are important besides dissemination of information including publication. It is no wonder, but no less gratifying, that special point was made to maintain the closest possible relations with institutions having similar aims in other regions throughout the world. As to research it was agreed that the organization should aim at the establishment of arrangements whereby national programmes may be encouraged and co-ordinated and methods and equipment standardized; but research projects should also be carried out by the organizing itself, including the operation of research vessels.

The organization should be established under joint sponsorship of UNESCO and FAO by means of a convention to be signed by the governments, within or without the area, which are interested in the development of oceanographic science in the region.

The governing authority should be a council of qualified scientists representing member governments, who may be assisted by advisers. The organization should be provided with a secretariat and, naturally, with the financial resources necessary for the carrying out of its functions. It was clearly realized that this secretariat might, for the time being, not be able to extend its activities to all functions suggested but would be obliged to limit its programme to the most essential matters. The Committee, however, believed that the programme should be an expanding one.

It was furthermore stressed that this secretariat should act in the closest liaison with the I.P.F.C., which is charged with similar responsibilities in the field of applied fisheries science, and that the secretariat, therefore, might most conveniently be located during the formative years as closely as possible to the seat of the I.P.F.C. (Bangkok) so that the most complete interchange of information and results may be

achieved ; likewise the organization might benefit, during that period, from the use of the library and documentation facilities of the I.P.F.C.'s secretariat.

A senior qualified scientific worker should be appointed as director of the organization and his salary suggested was to be 12,000 U.S. dollars. He should be assisted by an Executive Officer (8,000 U.S. dollars) while a further 15,000 U.S. dollars should be available for other assistance.

A committee consisting of Professor A. C. HARDY (chairman), Professor HANS PETTERSSON and PROFESSOR Th. MONOD were elected to draw up a panel of possible candidates for the directorship for the guidance of the appointing committee. I have no doubt that this committee will be very happy to have information about possible candidates.

In this brief survey I have attempted to give a summary of the results arrived at in Manila; I would like to add that there was a unanimous enthusiasm about the idea in general. Lively discussions only arose, when it came to the practical problem of *how* to start. Any oceanologist could conceive an ideal plan, but when the problem of money is introduced, restrictions are needed. The tentative budget for the first year was set at 100,000 U.S. dollars and for the second at 130,000 U.S. dollars. I feel this is a modest amount to spend on such an important and urgent problem, just to approach the level of our modest knowledge of the Atlantic Ocean for the Indian and Pacific Oceans. But we *must* get started. The success of the plan will depend upon the director to be found ; his scientific knowledge must be equally mixed both with enthusiasm and with responsibility towards the great task. These brief lines call for him.

ANTON FR. BRUUN
(Copenhagen)

Deep-Sea Research, 1954, Vol. 2, pp. 87 and 88. Pergamon Press Ltd., London.

Oceanography at the Eighth Pacific Science Congress

Quezon City, Philippines, 16-28 November

It is hardly surprising that the section on Oceanography has developed into one of the most important features of the Pacific Science Congresses, of which the first meeting was held in Honolulu in 1920. At the Seventh P.S.C. in New Zealand in 1949 a standing committee on the Oceanography of the Pacific was formed with Dr. Thomas G. Thompson, Seattle, as chairman and Dr. John P. Tully, Nanaimo, as secretary ; but considering the wide scope of this committee, for which the word oceanology perhaps would be more appropriate than oceanography, three sub-committees were formed at the same time, one on Physical Oceanography (chairman Dr. Koji Hidaka, Tokyo), one on Biological Oceanography (chairman Mr. A. W. B. Powell, Auckland, N.Z.) and one on the Fisheries (chairman Dr. Deogracias V. Villadolid, Manila). In this way the three main aspects of oceanology were at the same time left free but were fortunately linked together in a very useful way.

At the Eight P.S.C. the Organizing Chairman of Oceanography was the energetic Director of the Bureau of Fisheries, Manila, Dr. Deogracias V. Villadolid, who with his secretary, Mr. Teodoro G. Megia, had arranged a very full programme of lectures, symposia and excursions ; abstracts of all papers had been printed, so that everybody was able to prepare himself for the discussions – or to absent himself from a lecture so as to make himself available for private discussion.

Essentially this report intends to draw attention to the activity of this section, but those especially interested should read the abstracts or papers printed in the forthcoming *Proceedings*.

UNESCO had sponsored a special biological symposium on Marine Provinces in the Indo-Pacific Region, convened by Mr. A. W. B. Powell, Auckland, N.Z.

Other symposia were held on the General Circulation in the Pacific, Ecology of Coral Atolls, and on Productivity in Temperate and Tropical Waters.

A series of resolutions were drawn up and adopted by the Congress. Mention should be made of that which recommended the establishment of an Oceanographic Society of the Pacific, with a branch in each of several regions ; this should aim at promoting liaison between oceanographic investigators in the Pacific Area.

Furthermore the proposal, examined by a special meeting of consultants on oceanography, to create a legally constituted intergovernmental organization for oceanographic research in the Indo-Pacific Region, was strongly supported.

A suggestion was made of holding a symposium at the Ninth P.S.C. in Bangkok on the subject of recent changes in oceanographic and biotic conditions in the Pacific area; it would, naturally, be of great importance to have a similar investigation made whether changes as have occurred in the North Atlantic also may be traced in the Pacific.

Altogether the need for international collaboration, which was reflected from these resolutions, seemed to become more and more obvious each time oceanologists

met and the Eighth P.S.C. was itself a fine example of progress in this line.

While a copy of *Deep Sea Research*, No. 1, was circulated and studied with great interest, the readers of D.S.R. should study the Bathymetric Chart No. 6901 of the North-west Pacific, which was exhibited by Dr. K. Suda, Director of the Japanese Hydrographic Office. This very beautiful chart had been compiled and printed by the J.H.O. on 30 May, 1953, scale 1 : 8.000.000 (Lat. 35°N), contour interval 500 m ; colours and contours stand out in a magnificent way and a very pronounced relief effect is produced (see also Dietz, *Bull. Geol. Soc. Amer.*, Vol. 65, Pl. I.)

Dr. Thomas G. Thompson, who has served so well as the Chairman of the Standing Committee on Pacific Oceanography, desired to be relieved of his post and Dr. D. J. Rochford, Cronulla, N.S.W. was elected in his place, and in this way a close connection with the Indo-Pacific Fisheries Council was created because Dr. Rochford is the Chairman of Technical Committee I of the I.P.F.C.

The author of this report was present as a delegate of the Joint Committee of Oceanography of I.C.S.U., the activities of which also seemed to interest the P.S.C. Oceanography Section.

Anton Fr. Bruun (Copenhagen)

ANNOUNCEMENT

Commonwealth Oceanographic Conference

This Conference will take place from 18th-22nd October, 1954 at The National Institute of Oceanography, Wormley, Surrey. The main tasks of the Conference will be as follows :

To review the progress of oceanographic research within the Commonwealth in order to assess the value of broad planning of programmes.

To discuss what measures might be taken to promote the progress of oceanographic research and its widest practical extension throughout the Commonwealth.

To discuss what administrative arrangements it might recommend for facilitating the co-operative use by Commonwealth countries of the more expensive facilities required for oceanographic research, biological as well as physical and regional surveys.

To consider broad problems of oceanographic interest concerning the Commonwealth as a whole.

The " Discovery II " will be lying at No. 29 Berth, Shadwell Basin, and will be open for inspection by the Press, but not by the public, on the morning of 16th October. The time when she may be inspected has to be restricted as her stay in London is a very short one, and the ship's staff will be much taken up with loading of stores and equipment between two of the voyages in the very tight scientific programme which has to be completed.

Erratum

On page 256 of Vol. 1, at the end of the paper by John Northrop and Robert A. Frosch on " Seamounts in the North American Basin," the address should read " *Hudson Laboratories, Columbia University, Canada* " (*not* U.S.A.).

Deep-Sea Research, 1954, Vol. 2, pp. 89 to 92. Pergamon Press Ltd., London.

Volcanic ash-horizons in deep-sea sediments from the Eastern Mediterranean

OTTO MELLIS

Preliminary Report

IN 1948 the Swedish Deep-Sea Expedition with the *Albatross* collected a series of cores by means of the Kullenberg piston-core sampler. In some of these one or two ash-horizons were established. As seen from Table 1 the ash-horizons are present in the upper part of each core only. The cores were from 658 cm up to 958 cm long.

Table 1. *Cores from the eastern Mediterranean in which ash-horizons were found.*

	Station	*Core*	*Lat. N.*	*Long E.*	*Depth in m*	*Position of ash-horizons in the core in cm*
1	274	187	33 59	31 02	2500	39-40·5
2						88-89·5
3	275	188	33 55	30 17	2810	146·5-151
4						191·5-192·5
5	276	189	33 54	28 29	2664	0-2
6						102·5-104
7	278	190	33 54	26 10	2900	85·5-86·5
8	280	192	34 36	25 59	2680	0-4
9						206-207
10	283	194	34 48	23 29	3000	171-175·5
11	285	196	35 41	21 50	4270	126·5-127

The ash-horizons have a thickness of 1-4·5 cm ; under the microscope they are seen to consist of almost entirely colourless glass fragments. Crystallised minerals as *e.g.* pyroxene, plagioclase, biotite are rare.

In cores containing two ash-horizons (Core 187, 188, 189, 192) the refractive index of the glass fragments in the upper horizons is somewhat smaller ($n = 1{\cdot}51$) as in the lower ones ($n = 1{\cdot}52$). The difference is readily observed in the microscope. Where only one ash-horizon is present (Core 190, 194, 196), the refractive index of the glass fragments amounts to 1·52. Glass fragments with the index 1·51 are rich in gas bubbles and have the appearance of pumice (Fig. 1), whereas the glass fragments with a higher index (1·52) are plate-like and poor in gas inclusion (Fig. 2). When the cores are humid the difference between the two kinds is visible to the naked eye. The ash-horizons with glass of low refractive power appear lighter (mostly light-grey) than those containing glass with higher refraction which are brownish-grey. The difference in colour is probably due to the content of opaque mineral grains.

From these facts an attempt can be made to connect the upper ash-horizons in Cores 187, 188, 189 and 192. Analogously the lower ash-horizons in Cores 187,

188, 189 and 192 as well as the horizons 190, 194 and 196 may be comprised into a stratigraphical unit (Fig. 3).

Extending the attempt still further this comparison involves the origin of the ash. As the eastern Mediterranean is surrounded by many volcanoes there are various possibilities of interpretation limited by the relatively young date of these ash-horizons in the deep-sea sediments. In this connection it should be observed that the ash-horizons need not necessarily consist from aeolian-volcanic sediments. There is always a possibility that the primary aeolian-aquatic deposited ash has been re-stratified, although they need not have become transported very far, in which case the ash should have become mixed with terrigenous minerals and foraminifera-shells usually present in Mediterranean sediments. Besides, the two ash-horizons would not then retain their typical characteristics.

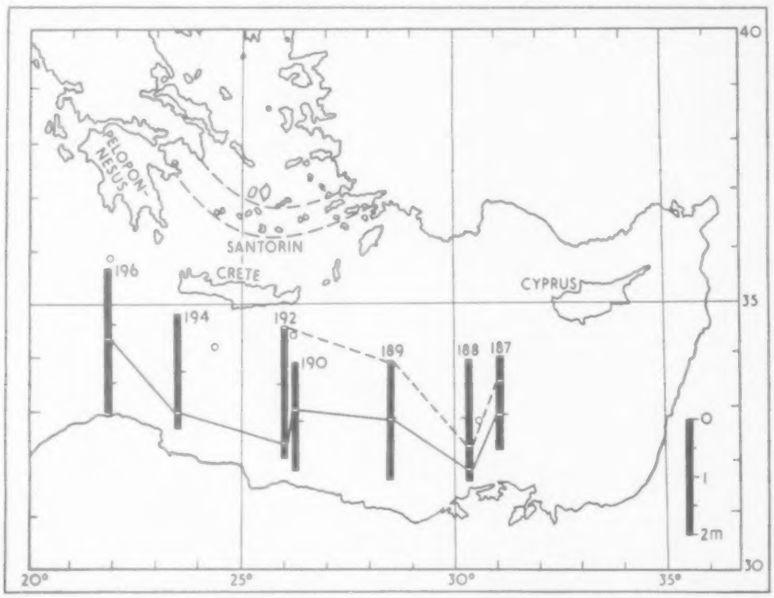

Fig. 3. Position of cores and ash-horizons (at the top end of profiles) in the eastern Mediterranean. The ash-horizons are white and connected with lines. Cores containing no ash-horizons are indicated by small circles.

Judging by data from geological literature on volcanic eruptions in the region of the eastern Mediterranean, the Santorin seems to be the most probable origin of the ash. According to FOUQUÉ (1879) and RECK (1936) the island-group of Santorin presents an ash-layer (" Pozzolana ") which has a thickness of 20-40 m. This ash-stratum suggests a mighty eruption of the Santorin which, according to archeological reports (WASHINGTON 1926 p. 355) has been " tentatively " dated to about 1800-1500 B.C. Such a violent eruption should have left traces in the deep-sea sediment of the eastern Mediterranean.

In addition, the composition of the ash speaks in favour of the assumption that at least the uppermost of the ash-horizons found is from the Santorin. The volcanic glass of the Santorin-ash from the eruption of 1800-1500 B.C. contains, according

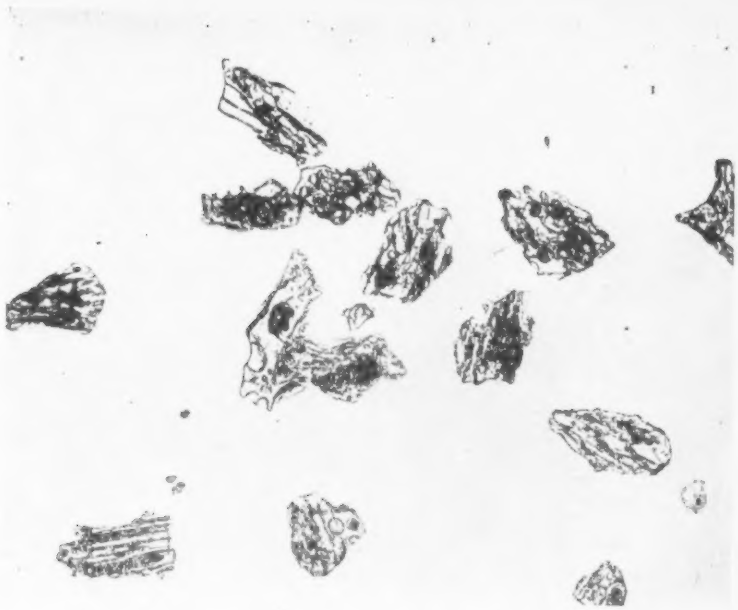

Fig. 1. Volcanic glass from the upper ash-horizon. Fraction 32-64μ. Core 187, Depth 39-40·5 cm. Enlargement 130 ×.

Fig. 2. Volcanic glass from the lower ash-horizon. Fraction 32-64μ. Core 187, Depth 87·5-89 cm. Enlargement 130 ×.

to Fouqué 71% SiO_2, *i.e.* it is acid in character. The refractive index of such a glass can be estimated at about 1·50-1·51 according to collocations by George (1925) and Mathews (1951). Merwin (13, p. 383) determined the refractive index of the glass to 1·515 in a lava sample from the Santorin. The ash from the great Santorin-eruption, the "Pozzolana," holds, according to Fouqué, beside glass only 3% of crystalline minerals like labradorite, oligoclase, hypersthene and augite. This corresponds to the properties found by me for the ash from the uppermost horizons of the cores. Labradorite and oligoclase (of somehwat variable composition) were found in all the samples examined. Hypersthene was found in a few samples only. According to Washington the content of hypersthene in lava from the Santorin has been exaggerated by earlier authors (Washington 1926 p. 382). This mineral does not often appear in the ash.

In the connection it should be observed that the characteristics of the Santorin-ash mentioned, holds also for products from other volcanoes in the Greek archipelago, which geologically and petrographically belong to the same dazitic-andesitic clan. The circumstance that no violent eruptions are known to have occurred from these volcanoes in historical time (Sapper 1927, Sonder 1924/25, Friedlander and Sonder 1924/25) seems to speak in favour of the Santorin. Also the volcanoes from Asia Minor may here come into question (Sapper 1927, Kennedy and Richey 1947) ; but very little is known about their activity and chemistry.

Provided that the upper ash-horizon of Cores 187, 188, 189 and 192 is derived from the Santorin-eruption of 1800-1500 B.C., an attempt can be made to estimate the rate of sedimentation in this part of the Mediterranean. A reliable calculation of the sedimentation rate cannot obviously be made for various reasons.

According to experience the uppermost part of the cores collected with the Kullenberg piston-core sampler is not always intact. Owing to the construction of the core sampler and the method of work the upper 10-30 cm of the core is sometimes lost.

By local, possibly seismically induced slumping the depth of the ash-horizon may have been more or less changed. A comparison with the bottom profile (Koczy), records from the expedition by echo sounding, indicates that Cores 189 and 192 were taken from the upper border of a slope so that a carrying away of the sediments originally deposited on top of the upper ash-horizon is probable. It may also be inferred from the bottom profile that Core 188 was raised from a trough and that the ash-horizon, possibly covered by sediment sliding down the slope, has been buried to a depth of 146·5 cm.

According to these considerations the sediment above the uppermost ash-horizon may be evaluated at 39-146·5 cm and the rate of sedimentation at about 10-30 cm in 1,000 years*). Here it is assumed that the ash comes from the Santorin-eruption of 1800-1500 B.C., that it was not re-stratified and that the rate of sedimentation since the eruption has been constant. This last presumption is naturally tentative in character.

As to the lower ash-horizon no certain conclusions can so far be given. However, accepting the above-mentioned rate of sedimentation and calculating from the sediment thickness above the lower ash-horizon, which varies between 80 and 200 cm,

* On the basis of the same material, Hans Pettersson estimates the rate of sedimentation in the eastern Mediterranean to 20-40 cm in 1,000 years (1954).

the age of the lower ash-horizon comes out at 3,000-7,000 years with a sedimentation rate of 30 cm in 1,000 years, and at 8,000-20,000 years with a sedimentation rate of 10 cm in 1,000 years. Taking the arithmetic mean of the sediment thickness above the lower ash-horizon equal to 130 cm, the corresponding figures become 4,000-13,000 years.

A preliminary mineralogical examination has not given any definite clue for determining the origin of this ash. The most important of its rare crystalline minerals are plagioclase, diopsidic pyroxene, green hornblende, biotite and ore-minerals. Hypersthene does not seem to be present in this ash-horizon, but sanidine is found in several samples. Considering the refractive index of the glass, equal to 1·52, the presence of sanidine and the estimated age of the ash, one is inclined to ascribe it to the great pre-historical eruption of the "Ur-Somma" (RITTMANN 1933), or even to the violent eruption of the "Archiphlegraeus" (RITTMANN 1951). As is well known, the latter eruption gave rise to the huge stratum (more than 400 m) of gray campanic tuff. Whether ash in such great quantities can have been transported through the air seems doubtful. Probably the ash comes from the Greek archipelago.

Future more searching mineralogical and chemical examinations are being undertaken, which I hope will throw more light on these questions.

For providing me with valuable material as well as for suggestions I wish to express my cordial thanks to Professor HANS PETTERSSON.

Appreciation is expressed to the late Mrs. KARIN JACOBSSON, Göteborg, for financial assistance.

University of Stockholm, Department of Minerology.

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Proposed names of features on the deep-sea floor

1. The Pacific Ocean

JOHN D. H. WISEMAN and CAMERON D. OVEY

Summary—The British National Committee on Ocean Bottom Features recommended to the International Nomenclature Committee that geographical names should be given wherever possible to all major features, and that personal or ships' names should only be given to secondary features where no suitable geographical name is available. At a meeting held in Monaco in September, 1952, the International Committee endorsed these proposals. The British Committee, in accordance with the general principles laid down by the International Committee, has prepared a list of names for the Pacific Ocean, extending to 50°S but excluding the East Indies. Only a few of the isolated elevations have been given provisional names because the Committee is at present considering the general principles which should govern the allocation of names to these features. The depths of the basins and trenches are based on soundings made available to the Committee.

INTRODUCTION

IT IS unfortunate that many of the existing names of deep-sea features were given without consideration of the basic principles of nomenclature. Some authors had a preference for personal names, whilst others considered that geographical names should be the rule. Frequently the geographical limits of a deep-sea feature were not given, and the descriptive term was ill-defined. As a result of this, there is considerable confusion in the literature and this has prevented a wider appreciation of the recent advances in knowledge of the deep-sea floor, made possible by technical developments. This confusion has also retarded investigation of deep-sea topography, and has made scientific discussion of this large area of the world's surface very difficult. At the VIIIth Assembly of the International Union of Geodesy and Geophyphysics held at Oslo, in 1948, the Association of Physical Oceanography established an International Committee with the object of formulating general principles and establishing international names. In order to crystallize British opinion a sub-committee of the British National Committee on Physical Oceanography was established. The present members of this Committee are: Dr. J. D. H. WISEMAN (Chairman), Dr. L. H. N. COOPER (Plymouth Marine Laboratory), Commander G. P. D. HALL (Hydrographic Department, Admiralty), Dr. H. F. P. HERDMAN (National Institute of Oceanography), Professor W. B. R. KING, F.R.S. (Department of Geology, Cambridge), Lt. Col. R. B. SEYMOUR SEWELL, F.R.S. (Department of Zoology, Cambridge), Professor J. A. STEERS (Department of Geography, Cambridge), and Mr. C. D. OVEY (Secretary). Detailed consideration has been given by this Committee to the descriptive terms and, as a result of this preliminary work, international agreement has been reached (WISEMAN and OVEY, 1953). The International Committee, at its meeting at Monaco during September 1952, stressed the desirability for any author, or chart making authority, before proposing a new name or term outside the 100 fms or 200 m contour, first to consult a national group. If this internationally agreed recommendation is adhered to, confusion in deep-sea nomenclature will be largely avoided.

HISTORICAL SURVEY

Possibly the first attempt to name Pacific deep-sea features was by PETERMANN (1877, pl. 7) who proposed personal or ships' names to thirteen deeps. MURRAY, J. (1895) and MURRAY and HJORT (1912, p. 129-43) favoured personal names for twenty-one Pacific deeps. The majority of the ridges or plateaux and seven of the basins were given geographical names. The Seventh International Geographical Congress at Berlin, in 1899, considered the desirability of international names for deep-sea features. Although no agreement was reached, KRÜMMEL (1901) suggested that the major features should be named in accordance with their geographical position, and that greatest depths and shallowest soundings should be given personal names. A similar recommendation was made by SUPAN (1899) who proposed that the names should be derived from the seas or the marginal countries. The first edition of the General Bathymetric Chart of the Oceans, compiled under the order of H.S.H. Prince ALBERT 1st of Monaco,and presented to the Académie des Sciences at Paris in January, 1904, and approved by the Eighth International Geographical Congress at Washington in September 1904, had the French translations of SUPAN's names. The policy of geographical names was partially abandoned in the second edition published between 1912-27, as personal or ships' names were given to many of the trenches and deeps: e.g. the " Ravin Japonais " became, in the 2nd edition, the " Fosse de Tuscarora." Also the names of some of the basins were replaced by the names of the seas, whilst some ridge names were deleted: e.g. in the 2nd edition the " Bassin du Japon " became the " Mer du Japon " and the " Crêtes des Mariannes " was deleted. In 1929 the International Hydrographic Conference instructed the International Hydrographic Bureau at Monaco to centralize oceanic echo-soundings, and to keep the General Bathymetrical Chart up-to-date. In all the most recent Pacific Sheets B_{ii}, B_{iii}, A_{ii}, A_{iii}, A'_{ii}, A'_{iii} issued between 1940-54, the deep-sea features are unnamed. The present policy of the International Hydrographic Bureau is to leave the features unnamed until international agreement is reached. In Sheet A'_{i}, published in 1936, four personal names were given to deeps in the Peru-Chile Trench.

SCHOTT (1935, pl. IV) and GROLL (1912) used geographical names for most of the features in the Pacific, whilst LEAHY (1938) used both geographical and personal names. WÜST (1936, taf. 4 and 1940, p. 124) gave the Pacific basins and trenches geographical names, and personal or ships' names to the deeps or greatest depths. Although an international committee, established in 1936, on the criteria and nomenclature of the major divisions of the ocean bottom failed to reach agreement, VAUGHAN (1940, p. 118) records that the consensus of opinion favoured geographical names. SVERDRUP, JOHNSON and FLEMING (1942, p. 1060) used geographical names for major deep-sea features.

Geographical names were given to the basins and trenches but personal or ships' names to the deeps on the bathymetrical chart of the North Pacific Ocean No. 5486 published by the U.S. Hydrographic Office in August, 1939 (BRYAN, 1940). In the " Bathymetric Chart Korea to New Guinea " U.S.H.O. Chart No. 5485 (HESS, 1948), as well as in the Oxford Atlas (LEWIS, CAMPBELL, BICKMAN and COOK, 1951, p. 14-15), geographical names were given to major deep-sea features.

REASONS FOR GEOGRAPHICAL NAMES

The British Committee considered that geographical names should be given wherever possible to all the major features of the deep-sea floor. Although this policy involves changing many well established names, abandons the law of priority in nomenclature and takes away from the discoverer of a new major feature the right of assigning a ships' or personal name, which he might reasonably consider it desirable to honour; the Committee considered that the arguments in favour of geographical names were overwhelming. These may be summarized as:—

(*a*) it is a great help to the memory and gives to the non-specialist an idea of the approximate position of the deep-sea feature;

(*b*) it is more logical and consequently facilitates discussion of these important features;

(*c*) international jealousy is not aroused and this makes possible international agreement;

(*d*) examples can be given where personal names have given place by common usage to geographical names;

(*e*) uncertainties about priority are avoided.

In view of these arguments the British Committee proposed to the International Committee that personal or ships' names should be given to secondary features provided no suitable geographical name was available, and that a reasonable survey has been made. It is the British Committee's view that the allocation of personal or ships' names to a few of the deepest soundings in the oceans would give encouragement to ships' captains and others. The International Nomenclature Committee, on 22nd September, 1952, endorsed the British Committee's proposals. It was also the view of that Committee that the length of a ridge can frequently be shown by two geographical names, e.g.: Eauripik – New Guinea Ridge. It is a useful convention to read from west to east, e.g.: Caroline – Solomon Ridge, and for features extending due north and south to quote the more northerly island first, e.g.: San Felix – Juan Fernandez Ridge.

DEEPS AND ISOLATED SECONDARY FEATURES

A deep, according to the internationally approved definitions (Wiseman and Ovey, 1953, p. 14), is " the well-defined deepest area of a depression of the deep-sea floor conventionally applied when soundings exceed 3,000 fms." It is the British Committee's view that the existing deeps should not be renamed in accordance with the rules of geographical nomenclature, because a deep from a morphological point of view is relatively unimportant. The British Committee recommends that newly discovered deeps should remain unnamed, and in their opinion this term should gradually fall into abeyance. The British Committee has purposely omitted from its list the names of the deeps in the Pacific Ocean.

A seamount is " an isolated or comparatively isolated elevation of the deep-sea floor of approximately 3,000 ft or more " (Wiseman and Ovey, 1953, p. 15). The International Committee considered that a seamount should only be named when adequately surveyed, and the British Committee is at present considering the principles which should govern the allocation of names to secondary elevations of the deep-sea

floor. The examples given in the Pacific have therefore been limited to those where there is detailed published information.

PROPOSED NAMES

The British Committee issued in the Spring of 1951 its first provisional list of names for Pacific deep-sea features. This list was submitted to authorities outside Great Britain, and has been revised from time to time. The list given below was approved by the British Committee, which gratefully acknowledges help from many sources, but in particular from the Hydrographic Department of the Admiralty; the U.S. Hydrographic Office; the U.S. Coast and Geodetic Survey, and the International Hydrographic Bureau. The British Committee is not aware of any recent compilation of greatest depths for the Pacific basins and trenches, and it hopes that the publication of these depths will emphasize the scientific importance of taking continuous echo-profiles across these structural features of the earth's surface.

It is unfortunate that there is no uniform policy amongst chart making authorities about correcting echo soundings for the speed of sound in sea-water. The British Hydrographic Department, as well as the U.S. Coast and Geodetic Survey corrects soundings by the use of MATTHEWS' (1939) tables for the speed of sound in sea-water, whilst the U.S. Hydrographic Office normally refers soundings to a constant velocity of 4,800 ft./sec. This divergence of policy leads to many errors of fact, and in consequence the British National Committee decided to include a definite statement when it is known that a sounding has been corrected for the speed of sound in sea-water. Although the International Committee (*Bull. d'Inform. de l'U.G.G.I.*, 1953, No. 1, p. 128) decided that the existing practice of correcting soundings should be continued, the British Committee has at this stage, been unable to carry this policy into effect for all the greatest depths in the Pacific basins and trenches.

The British Committee would welcome any corrections to the depths or co-ordinates, or of the existence of greater depths which have not been brought to its notice. They would also welcome reasoned criticisms of the proposed names or geographical limits, as well as proposals for new names, especially if they have the support of a national group and are within the framework of the general principles approved by the International Committee. Such criticisms should be sent at an early date to the Joint Secretaries of the International Nomenclature Committee (Admiral J. D. NARES and Mr. C. D. OVEY).

(1) *Ridges or Rises*

1. *Aleutian Ridge*

   Extends along the Aleutian Island chain from approximately 56°N 164°E to Unalaska Island.

   A detailed bathymetric chart of the ridge in the neighbourhood of Kiska Island has recently been published (GIBSON and NICHOLS, 1953). This chart shows many submarine canyons, valleys and elevations, as well as a clearly defined deep-sea terrace. Sections across the southern slope of the Aleutian Ridge are also given by MURRAY, H. W. (1945).

2. *Austral Ridge*

   Extends along the length of the Austral Islands.

3. *Bonin Ridge*
A north–south ridge extending from about 28°40′N 142°10′E to 25°50′N 142°10′E. The ridge rises from a general depth of 1,500 fms.

4. *Caroline–Solomon Ridge*
This is a broad ridge extending eastward from approximately 9°N 139°E through the Caroline Islands, and then in a southerly direction towards the Solomon Islands. The ridge rises from a general depth of 1,500-2,000 fms, and the Caroline Islands are situated on the western portion of it.

5. *Eauripik–New Guinea Rise*
This is a broad, north–south rise extending southward from Eauripik Atoll to New Guinea (HESS, 1948, p. 423).

6. *Hawaiian Ridge*
Extends along the entire length of the Hawaiian Islands from approximately 30°30′N 177°30′E to 19°30′N 154°W. Many elevations some forming islands rise from a general depth of 2,000 fms. A bathymetric chart of a portion of this ridge has been given by STOCKS (1950).
The ridge is apparently superimposed on the axis of the Hawaiian Rise which north-west of Midway Island has a width of approximately 600 miles (DIETZ and MENARD, 1953; DIETZ, MENARD and HAMILTON, 1954).

7. *Hunter Island Ridge*
A ridge running south-westward from the Fiji Islands to Hunter Island.

8. *Kermadec Ridge*
Extends from approximately 26°S 178°W to 34°S 180°W.

9. *Kuril Ridge*
Extends along the length of the Kuril Islands.

10. *Kyushu–Palau Ridge*
This ridge extends with gaps in a southerly direction from 30°20′N 132°50′E to the Palau Islands. It then continues in a south-westerly direction to 5°N 132°E.

11. *Lord Howe Rise*
Extends from approximately 23°S 160°E in a general south-easterly direction to New Zealand (BRODIE, 1952, p. 374).

12. *Marcus–Necker Rise* (*formerly Mid-Pacific Mountains*)
Extends with some gaps in an easterly direction from near Marcus Island to Necker Island. Many elevations rise from a general depth of 2,000 fms. Part of the ridge was surveyed by the Midpac Expedition (DIETZ and MENARD, 1953; DIETZ, MENARD and HAMILTON, 1954). According to these authors there are numerous large volcanic seamounts, many with flat tops, superposed on a low rise. The tops of these tablemounts are at a depth of 700-900 fms, and the side slopes are concave upwards with a maximum slope of about 20° near the top. Reef corals, indicating a Cretaceous age (HAMILTON, 1953), have been recovered from two of the tablemounts. It is probable that this ridge extends westward to Marcus Island.

DIETZ and MENARD (1953) proposed the name Mid-Pacific Mountains for this ridge. The British Committee considers that this name is confusing. By comparison with the Mid-Atlantic Ridge it would suggest a longitudinal ridge. The name Marcus–Necker Ridge has the advantage of giving its location and is in accordance with the general principles of nomenclature.

13. *Marianas Ridge*
Extends from approximately 22°30′N 143°10′E through the Mariana (Guam and Saipan), Islands, to 12°N 144°30′E. The ridge rises from a general depth of 2,000 fms at its western base.

14. *Nansei Shoto Ridge (formerly Ryukyu Ridge)*
Extends from Taiwan to Kyushu and includes the Nansei Shoto Islands.

15. *New Hebrides Ridge*
The NNW–SSE ridge on which the New Hebrides are situated. Extends from approximately 10°S 166°E to 21°S 170°E. The general base of this ridge is at a depth of 1,000 fms.

16. *Norfolk Island Ridge*
Extends in a southerly direction from about 25°S 168°E through Norfolk Island to about 34°S 170°E (BRODIE, 1952).

17. *North Rat Island Ridge*
A curved ridge about 60 miles wide extending northward for approximately 300 miles from the Rat Islands (Aleutian Archipelago). The ridge has for the greater part of its length a ridge-depth of less than 500 fms (MURRAY, H. W., 1945, p. 780).

18. *North-west Christmas Island Ridge*
Extends from Christmas Island in a north-west direction to Kingman Reef and then in a northerly direction to a point about 10°N 162°W. Several elevations rise from a general level of 1,500 fms.

19. *Pacific–Antarctic Ridge*
A broad ridge extending from about 40°S 112°W to approximately 65°S 180°W.

20. *San Felix–Juan Fernandez Ridge*
Extends in a southerly direction from San Felix Islands to Juan Fernandez Islands. Prolongations of this ridge occur both in northerly (18°S) and southerly (41°S) directions.

21. *Society Ridge*
Extends along the length of the Society Islands.

22. *Solomon Islands Ridge*
The ridge defined by the 1,000 fms contour on which the Solomon Islands are situated.

23. *South Fiji Ridge*
A ridge extending southward from the Fiji Islands to about 30°S 180°E.

24. *South Honshu Ridge*
Extends south from Honshu approximately to 12°N 142°E. The general foundation of this ridge is at a depth of 2,000 fms (HESS, 1948). Elevations rise from this ridge and in places form active volcanoes: e.g. Myojin-Sho (NIINO, 1953).

25. *South Tasmania Ridge*
Extends in a southerly direction from the south tip of Tasmania to about 50°S.

26. *Tonga Ridge*
Extends from approximately 15°S 174°W to 24°30′S 176°30′W.

27. *Tuamotu Ridge*
Extends along the length of the Tuamotu Islands.

28. *Woodlark Ridge*
The ridge extending from D'Entrecasteaux Islands, through the Woodlark Islands towards Bougainville.

29. *Yap Ridge*
Extends in a north-easterly direction from approximately 7°20′N 135°45′E to 11°10′N 138°30′E. Yap Island and Nuglu Atoll are situated on the ridge. The ridge rises from a general depth of 2,000 fms.

(2) *Plateaux*

1. *Albatross Plateau*
The large elevated area which is bounded approximately by 110°W and 5°S and on the east by the Guatemala Basin.

2. *South-eastern Pacific Plateau*
The large broad elevated area which extends roughly from 10°S to 40°S extending in the west towards the Tuamotu Islands and in the east towards Juan Fernandez Islands.

(3) *Tablemounts* (Guyots)

1. *Erben Tablemount* 225/2,300 *fms* 32°50′*N* 132°32′*W*
Discovered in 1874 by U.S.S. *Tuscarora.* Surveyed in 1948 by U.S.S. EPCE (*R*) 857 when deep-sea photographs and rock samples (olivine basalt) were taken. A contoured chart down to a depth of 1,000 fms is given by CARSOLA and DIETZ (1952).

2. *Fieberling Tablemount* 230/2,300 *fms* 32°24′*N* 127°47′*W*
Discovered in 1936 by U.S.S. *Ramapo.* Surveyed in 1947 by U.S.S. *Fieberling.* Further investigations by U.S.S. EPCE (*R*) 857 in 1948, when deep-sea photographs and rock samples (olivine basalt) were taken. The flanks have an average slope of 18°. A contoured chart down to a depth of 1,000 fms is given by CARSOLA and DIETZ (1952).

(4) *Seascarp*

1. *Mendocino Seascarp*

According to Menard and Dietz (1952) this feature extends westward from Cape Mendocino, California for at least 1,200 miles. Its height about 70 miles from the shore is 10,500 ft. and 1,000 miles from the shore 8,400 ft. The maximum average slope is 7-10°, but portions have a slope 18-24°. The seascarp lies on the south side of the ridge, which has a gentler slope towards the north. Regional bathymetry shows that the sea-floor for hundreds of miles south of the ridge is about 800 fms deeper than the sea floor for hundreds of miles north.

(5) *Basins*

1. *Aleutian Basin*

Bounded on the south by the Aleutian Ridge. Greatest depth 2,863 fms, 5,236 m 53°52′N 177°37′W. Sounding corrected by Matthews' (1939) tables. The uncorrected sounding taken by U.S.S. *Blackfin* (SS332) in 1947 was 2,800 fms with a velocity of 4,800 ft./sec.

The sounding 3,970 fms, 7,260 m 54°36′N 170°18′E shown on U.S.H.O. Chart 0068, April 1946, is probably erroneous, according to a recent communication from the U.S. Hydrographic Office.

2. *Coral Sea Basin*

Bounded on the east by the ridge extending from Chesterfield Reefs to Rennell Island and westward to the south-eastern tip of New Guinea. Greatest depth 2,580 fms, 4,718 m, 13°17′S 149°36′E. U.S. H.O. Chart 0826.

On the General Bathymetric Chart of the Oceans, Sheet A'_{III}, there is a sounding of 4,899 m, 2,678 fms, at approximately 13°57′S 152°18′E. This sounding originates from French Chart no. 2B, *Planisphère Terrestre*, 3rd Edition, May 1939, but is not shown on H.O. Charts 2483, 2683, 2759A and 2764.

3. *East Caroline Basin*

Bounded on the north and on the east by the Caroline–Solomon Ridge; in the west by the Eauripik–New Guinea Rise; Greatest depth 3,784 fms, 6,920 m, 0°37′N 148°44′E. Japanese Chart 6901.

4. *East China Basin*

Bounded on the south by Formosa and on the south-east by the Nansei Shoto Ridge. Greatest depth 1,487 fms, 2,719 m, 25°16′N 124°01′30″E. Japanese Navy Chart 1203, April 1932.

5. *Great Pacific Basin*

Bounded on the north-west by the Kuril Ridge; on the west by the South Honshu Ridge and Marianas Ridge; on the south by the Caroline–Solomon Ridge, New Hebrides Ridge, the Tuamotu Ridge, and on the east by the Albatross Plateau, and South-eastern Pacific Plateau. Greatest depth 4,113 fms, 7,521 m, 1°23′N 173°00′W. U.S.H.O. Chart 5486.

6. *Guatemala Basin*
The basin south-west of Guatemala. Bounded on the south-west by the Albatross Plateau. Greatest depth 3,107 fms, 5,682 m, 10°48′N 92°43′W U.S.H.O. Chart 0526.

7. *Japan Basin*
Bounded on the south by Japan. Greatest depth 2,207 fms, 4,036 m, 38°51′30″N 136°47′00″E. Japanese Navy Chart 1154, July 1934.

8. *Kuril Basin*
Bounded on the south-east by the Kuril Ridge. Greatest depth 2,849 fms, 5,211 m, 47°25′N 146°55′E. U.S.H.O. Chart 0529.

9. *New Britain Basin*
Bounded on the north by the islands of New Britain and Bougainville; in the south-west by New Guinea; on the South-east by the Woodlark Ridge. Greatest depth 2,963 fms, 5,419 m, 7°51′S 151°25′E. H.O. Chart 2764, July 1938.

10. *New Caledonia Basin*
Bounded in the north by New Caledonia; on the west by the Lord Howe Rise; on the east by the Norfolk Island Ridge. Greatest depth 2,199 fms, 4,021 m, 28°8·2′S 166°13′E (*Beiheft zu den Nachrichten für Seefahrer*, 1930, No. 10). Taken by German Cruiser *Emden* in June 1929).

11. *New Hebrides Basin*
Bounded on the north by the Solomon Islands Ridge; on the east by the New Hebrides Ridge; on the south by New Caledonia, and on the west by the ridge extending from Chesterfield Reefs to Rennell Island, and westward to the south-eastern tip of New Caledonia. Greatest depth 3,314 fms, 6,061 m, 12°30′S 166°07′E. From various general charts.

12. *North Fiji Basin*
Bounded on the north by a group of islands extending along a line of latitude of approximately 11°30′S; on the west by the New Hebrides Ridge; on the south by the Hunter Island Ridge. Greatest depth 2,714 fms, 4,963 m, 16°35′S 176°34′E. Sounding corrected by Matthews' (1939) tables. The uncorrected sounding, taken by H.M.S. *Challenger* on 10th September 1951, was 2,704 fms with a velocity of 4,920 ft./sec.

13. *Philippine Basin*
Bounded on the north by the Nansei Shoto Ridge; on the west by the Philippines; and on the east by the South Honshu Ridge. Greatest depth 4,092 fms, 7,483 m, 16°13′N 130°30′E. Sounding corrected by Matthews' (1939) tables. The uncorrected sonic sounding was 3,925 fms with a velocity of 4,800 ft./sec. U.S. H.O. Chart 5485.

14. *South-eastern Pacific Basin*
Bounded on the north by the Albatross Plateau; on the west and south by the South-eastern Pacific Plateau. Greatest depth 2,897 fms, 5,298 m, 14°50′S 98°05′W. U.S.H.O. Chart 0823.

15. *South Fiji Basin*
Bounded on the north by the Hunter Island Ridge; on the west by the Norfolk Island Ridge; in the east by the South Fiji Ridge and the Kermadec Ridge. Greatest depth 2,900 fms, 5,303 m, 25°05′S 172°56′E. From various general charts.

16. *South-western Pacific Basin*
Bounded on the north roughly by 15°S latitude; on the west by the Kermadec and Tonga Trenches as well as New Zealand; on the east by the South-eastern Pacific Plateau, and on the south by the Pacific-Antarctic Ridge. Greatest depth (Byrd Depth) 4,692 fms, 8,581 m, 61°06′S 179°00′E. The Byrd depth was obtained in 1932 by the first Byrd Antarctic Expedition aboard the S.S. *Bear of Oakland*. The sounding was corrected according to the U.S.H.O. by an extrapolation of Matthews' (1939) tables. Leahy (1938, p. 105); Sverdrup *et al.* (1942, p. 1060); Fleming (1952, p. 107). This sounding is not shown on Admiralty Charts, nor is it on U.S.H.O. Chart 2562, issued in November, 1947. In the British Committee's view the validity of the Byrd Depth is questionable, and this area should be reinvestigated. Nevertheless it should be noted that the *Bear of Oakland* is reported to have obtained several soundings greater than 4,000 fms, between 60° and 61°S*.

(6) *Trenches*

1. *Aleutian Trench*
A narrow elongate depression of the deep-sea floor running parallel to the convex south side of the Kenai and Alaska peninsulas and the Aleutian archipelago. It extends for a distance of 2,200 miles from Yakutat Bay in the Gulf of Alaska westward to Attu Islands. The minimum depth of the trench below the floor of the Pacific ranges from 200 fms south of Cape Elias to 1,600 fms off Umnak Island. The average slope of the north face of the trench is 3-4° (locally it may exceed 30°) and in many places the side slopes of the trench meet in a narrow area. The south side has an average slope of 1-2°. There is an approximate difference of about 28,000 ft. between conspicuous mountain features and the floor of the trench through its entire length. The bottom of the trench is flat off Kiska Island and is about five nautical miles in width. (Murray, H. W., 1945; Gibson and Nicholls, 1953). Greatest depth 4,199 fms, 7,679 m, 51°13′N 174°48′E and at 51°49′N 172°20′E. This is an uncorrected sounding taken by the U.S. Coast Guard Cutter *Chelan* in 1936 with a velocity of 4,920 ft./sec. Matthews' (1939) tables do not extend sufficiently to give a correction.

2. *Bonin Trench*
Extends in a south-easterly direction from near the Bonin Islands to 21°N. The trench is roughly defined by the 3,500 fms contour. Greatest depth 5,007 fms, 9,156 m, 24°17′N 143°23′E. Sounding corrected by Matthews' (1939) tables. The uncorrected sonic sounding taken by U.S.S. *Salt Lake City* was 4,760 fms with a velocity of 4,800 ft./sec. U.S.H.O. Chart 5485.

At a nearby locality 23°49·9′N 144°00·3′E the *Carnegie* took a sounding of 4,730 fms, 8,650 m. This corrected sonic sounding was obtained on 29th May 1929, Cruise VII, Oceanographic Station No. 109.

* See author's note, p. 106.

3. *Guatemala Trench*
Situated close to the Pacific coast of Guatemala. The trench extends from approximately 15°N 95°W to 12°N 90°W. Greatest depth 3,643 fms, 6,662 m, 14°02′N 93°39′W. Sounding corrected by Matthews' (1939) tables. The uncorrected sonic sounding taken in 1952 by U.S.S. EPCE (*R*) 857 was 3,510 fms, with a velocity 4,800 ft./sec.
At a nearby locality 13°57′N 93°54′W a sounding of 3,548 fms, 6,489 m, is shown on U.S.H.O. Chart 932, November, 1932.

4. *Japan Trench*
Extends in a southerly direction from about 40°N to 26°30′N. The trench is roughly defined by the 3,500 fms contour. Greatest depth 5,771 fms, 10,554 m, 30°30′N 142°30′E. This sounding according to the U.S.H.O. was corrected by the use of the factor 1·049 of *Carnegie* station 113 (*Carnegie* Cruise VII, 1928-29). The uncorrected sounding taken by the U.S.S. *Ramapo* on the 30th Arpil 1933 using an audible frequency apparatus was 5,502 fms. U.S.H.O. Pub. 210c. Hess and Buell (1950, p. 405) consider the *Ramapo* Depth spurious, and suggest that it is a side echo. They state that the maximum depth of the trench is probably 5,673 fms, but no coordinates are given. The 5,673 fms sounding was obtained on a traverse nearly at right angles to the axis of the trench. Wüst (1951) is in agreement with the assessment given by Hess and Buell. On U.S.H.O. Chart 5485 issued in October 1946 the *Ramapo* Depth is omitted. The U.S. M/V *Spencer F. Baird* has recently reinvestigated this area (Fisher, 1954). The deepest sounding 5,255 fms, 9,611 m, was taken by a modified EDO high-frequency echo-sounder at 30°54·5′N 142°16·5′E, and corrected from hydrographical measurements (a 3,440 fms cast 70 miles north in the trench). Fisher states that this sounding may be a slope echo return, and that the trench floor may be deeper than 5,255 fms.

5. *Kermadec Trench*
Situated to the east of the Kermadec Ridge. Extends from approximately 26°S to 36°S, with possible continuation to 42°30′S. Greatest depth 5,465 fms, 9,994 m, 31°53′S 177°05′W. Sounding corrected by Matthews' (1939) tables. The uncorrected supersonic sounding taken on 2nd March 1952 by the *Galathea* was 9,700 m with a velocity of 1,500 m/sec.

6. *Kuril Trench*
A narrow elongate depression of the deep-sea floor running south-west from Beringa Is. parallel to Kamchatka and the Kuril Is. and terminating near Hokkaido. The trench in its deeper portion is defined by the 3,500 fms contour. Greatest depth 5,243 fms, 9,587 m, 44°57′N 152°22′E. Japanese Chart 6901, March 1952. The Russian research ship *Vityaz* has discovered, according to Tass Agency, a greatest depth of 5,674 fms, 10,377 m, but no position is given.

7. *Marianas Trench*
Situated on the east and south sides of the Marianas Ridge. The trench is roughly defined by the 3,500 fms contour, and extends from about 20°15′N 147°10′E to 10°50′N 140°45′E. Cross-sections of the trenches are given by Gaskell, Swallow and Ritchie (1953). The greatest oceanic sounding—the

Challenger Depth – occurs in this trench (Carruthers and Lawford 1952). Greatest depth 5,940 fms, 10,863 m, supersonic sounding corrected by Matthews' (1939) tables. 11°19′N 142°15′E sounding taken by H.M.S. *Challenger* in October 1951.

The deep-sea sediment near the greatest depth is rich in the diatom *Ethmodiscus rex* (Wiseman and Hendey, 1953).

8. *Nansei Shoto Trench (formerly the Ruykyu Trench)*
Situated on the south-east side of the Nansei Shoto Ridge. The trench is roughly defined by the 3,500 fms contour. Greatest depth 4,105 fms, 7,507 m, 25°15′N 128°32′E. Sonic sounding obtained by Japanese vessel *Mansyu* in November 1925. Records of Oceanographic Works in Japan, **6**, No. 1, March, 1934.

9. *New Britain Trench*
Situated to the south of New Britain and Bougainville Islands. Greatest depth 4,998 fms, 9,140 m, 6°35′S 153°53′E. General Bathymetric Chart of the Oceans, A'_{iii}, May 1942.

10. *New Hebrides Trench*
Situated to the south-west of the New Hebrides. Extends from about 17°S to 21°20′S. Greatest depth 3,773 fms, 6,900 m, 20°41·5′S 168°41′E. French chart 4310, 1948 ed. with block correction in 1951.

11. *Palau Trench*
Situated to the south-east of the Palau Islands. Greatest depth 4,450 fms, 8,138 m, 7°40′42″N 135°04′36″E. Sounding taken by German Cable Ship *Stephan* on 6th March 1905.

12. *Peru-Chile Trench*
Situated to the west of Peru and Chile. Extends from about 8°S to 33°30′S. Greatest depth 4,175 fms, 7,634 m, 25°42′00″S 71°31′40″W. Sounding taken by Cable Ship *Relay* of the Central and South America Telegraph Company on 16th May 1890. U.S.H.O. Pilot Chart 2601.

13. *Phillipine Trench*
Situated on the east side of the Philippines. Extends from approximately 14°10′N 125°15′E to 3°45′N 128°45′E and is roughly defined by the 3,500 fms contour. Greatest depth – *Cape Johnson* Depth – 5,740 fms, 10,497 m, 10°27′N 126°36′E. Sounding corrected by Matthews' (1939) tables. The uncorrected sounding taken by U.S. *Cape Johnson* on 14th July 1945 was 5,420 fms, with a velocity of 4,800 ft./sec (Hess and Buell 1950, p. 404). The British Committee has been informed by Dr. Bruun that the sounding taken by the *Galathea* (Bruun, 1951) 5,763 fms, 10,540 m, 10°23·8′N 126°40·5′E is erroneous, as the correction was inadvertently made on the assumption that the standard velocity was 1,463 m/sec. whereas it was 1,500 m/sec. The corrected greatest depth obtained by the *Galathea* on 2nd March 1952 is therefore 5,613 fms, 10,265 m. Sounding corrected by Matthews' (1939) tables. Dr. Bruun considers that this sounding is surprising as the *Galathea* was cruising around the position of the *Cape Johnson* Depth, and smaller depths were obtained in the neighbourhood of the *Emden* Depth.

14. *Tonga Trench*
Situated on the east side of the Tonga Islands. Extends from about 14°30′S 173°40′W to approximately 26°S 175°W. Greatest depth – the *Horizon* Depth – 5,814 fms, 10,633 m, 23°15·5′S 174°46·5′W. Sounding corrected from hydrographical measurements from a deep cast in a comparable environment 200 miles away. Sounding taken by U.S. M/V *Horizon* during December 1952 by the explosive oscillograph method, and is a minimum sounding of the greatest depth (FISHER, 1954). The maximum depth of the trench is considered to be at least 5,900 fms. A bathymetric chart is given in the Shipboard Report of the Capricorn Expediton (Reference: 53-15 Scripps Institution of Oceanography).

15. *Yap Trench*
Situated to the east of the Yap Ridge. The trench extends from approximately 10°45′N 139°35′E to 7°15′N 135°40′E. Greatest depth 4,701 fms, 8,597 m, 10°18′N 139°00′E. Japanese Chart 6901.

British Museum (Natural History), London.

Department of Geography, Cambridge

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Authors' Note—The following three Basins should be added to those quoted on page 102:

17. *Tasman Basin*
Bounded on the east by the Lord Howe Rise; on the south east by the ridge extending from the south tip of New Zealand to Macquarie I., and on the west by the South Tasmania Ridge. Greatest depth 3,250 fms, 5,944 m, 33°10′S 153°19′15″E. H. O. Chart 3622, Jan. 1922. Sounding taken by H.M.S. *Penquin*, 15th December 1896.

18. *West Caroline Basin*
Bounded on the north by the Caroline–Solomon and the Yap Ridges; on the east by the Eariupik–New Guinea Rise. Greatest depth 3,170 fms, 5,798 m, 4°29′N 136°16′E. Japanese Chart 2112, 1937.

19. *West Marianas Basin*
Bounded on the west by the South Honshu Ridge and on the east by the Marianas Ridge. Greatest depth 3,058 fms, 5,592 m, 20°20′N 143°02′30″E. U.S.S. *Ramapo*, route no. 19, Jan. 1932. U.S.H.O. Pub. 210c. Uncorrected sonic sounding 2,963 fms, velocity 4,800 ft./sec.

Deep-Sea Research, 1954, Vol. 2, pp. 129 to 148. Pergamon Press Ltd., London.

Oscillations in sea temperature at Scripps and Oceanside Piers

ROBERT S. ARTHUR

Summary—Observations of sea temperature have been made in the vicinity of two southern California coastal piers some 40 km apart. Temperature-depth curves and temperature profiles show a shallow thermocline during the warm months. The depth of the thermocline varies with time, and, as a result, thermograms from fixed depths at the pier ends show oscillations. Changes of 5 C over a time interval of hours (Fig. 1) are frequent as the intersection of the thermocline with the sloping bottom moves inshore and offshore.

Thermograms from the two piers show no obvious coherence in the oscillations, but over a distance of 4 km along the Scripps shore there is evidence of coherence. Oscillations in the thermograms suggest the possibility of tidal periodicities but without the persistent regularity demonstrated for surface tides. An internal wave mechanism is consistent with the data. Internal waves have been confirmed in deeper water in the general area, and the oscillations can, therefore, represent the effect near the shore of internal waves of various periods, including tidal.

Applications to marine biology, underwater sound, and sedimentation are mentioned. It is suggested that coastal piers offer bases for economical operation of gauges which will help to determine the existence and nature of internal-tide waves.

INTRODUCTION

AT various times during the last 30 years records have been made of the temperature of water near the sea bottom and surface at the end of Scripps Pier, La Jolla, California (see Fig. 6 for location). Traces of temperature against time on the resulting thermograms show oscillations, and the records exhibit features characteristic of wide-band spectra with periods ranging from minutes to many hours. Prominent, even without smoothing, are " peaks " and " dips " separated by time intervals ranging from several hours to and including tidal intervals, and only these oscillations are considered in the ensuing discussion. The temperature of the water near the bottom may change by 5 C and, then, return to the original value some hours later. Variations of this magnitude occur only during the summer months when there exists near the surface a pronounced vertical gradient in temperature. A comparison of curves of temperature against depth as shown in Fig. 1 indicates the type of change discussed in the present paper.

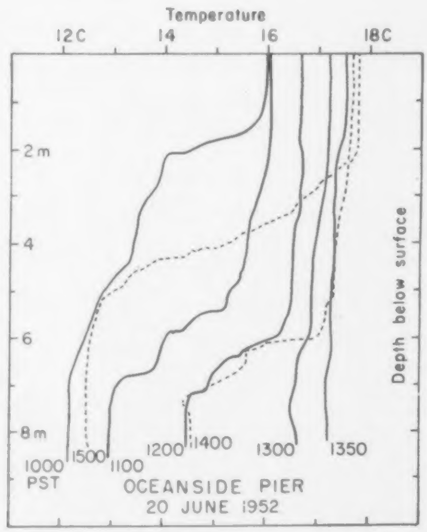

Fig. 1. Temperature-depth curves at indicated times (Pacific Standard) from BT lowerings at 140 m from pier end. Dashed curves reveal inflow of colder water at depth. LEIPPER (1950) shows a similar figure for Scripps Pier.

LEIPPER (1950) has made a detailed study of temperature records from the end of Scripps Pier and of bathythermograph (BT) records from the vicinity. He discusses a number of factors which may influence the sea-temperature variations in the Scripps area and emphasizes the importance of stirring of the stratified water and subsequent oscillating movements associated with tidal currents over an irregular bottom. HUBBS (1954) has floated a temperature-sensitive element and shown that the magnitude of the oscillations is very greatly reduced at the sea surface. DEFANT (1950b) has made a harmonic analysis of one of the thermograms presented by LEIPPER. He implies that the oscillations in the record are produced by internal waves of tidal period, which he designates more briefly as internal tides.

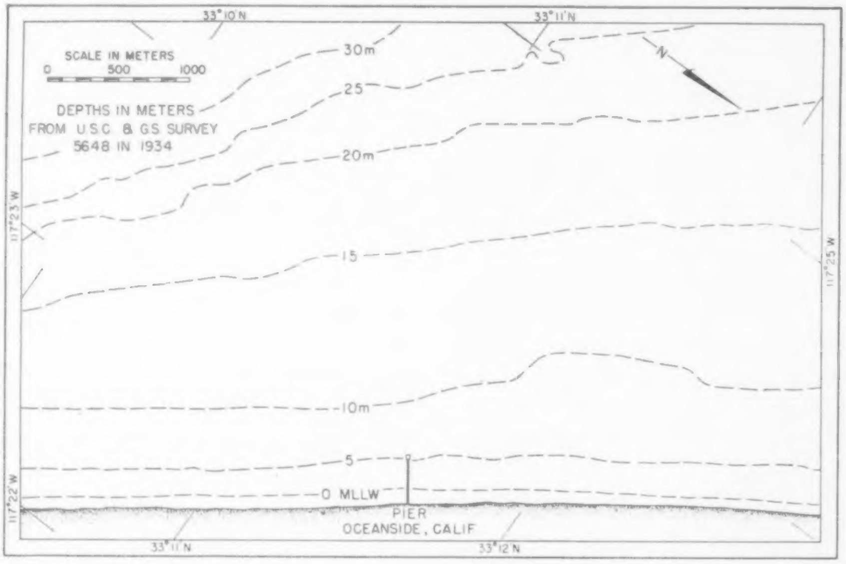

Fig. 2. Topography in Oceanside area. Since 1934 survey erosion has occurred along shore and depth increased along pier.

In the summer of 1952 several series of bathythermograms (Fig. 1) were obtained along the pier at Oceanside, California. Temperature oscillations of large amplitude were found in this location, where bottom topography is very regular in contrast to the Scripps area (compare Figs. 2 and 6). Beginning in June of 1953 thermographs were operated at both piers and additional observations were made in the vicinity of Scripps Pier. The extension of the observations in space makes possible a more complete description of the temperature variations.

A schematic model of the variations is presented first, and, then, data on which the model is based are given. Next, there follows a discussion of various features of the temperature oscillations and of factors which influence them. All observations have been made in shallow water, but it is likely that the phenomenon is related to deep-sea temperature changes as suggested by DEFANT.

A SCHEMATIC MODEL

Temperature Profiles. Isotherms in a vertical section normal to shore are shown at

three different times in Fig. 3 (top row). The spacing of the isotherms exhibits a feature characteristic of summer conditions in the area. Below the sea surface there is a *thermocline layer* where the vertical temperature gradient is large relative to the gradient above and below. Within this layer, the surface which coincides with the maximum gradient is the *thermocline*.

The isotherms in the model section rise 5 m in 6 hrs and, afterwards, return to their original depths. As a consequence, the intersection of the thermocline with the sloping bottom moves towards shore and, then, away from shore. The sea level exhibits a tidal change of 1 m. No particular significance is to be attached to the phase coincidence in rise and fall of sea level and isotherms or the time interval of 12 hours, at least until actual data in a following section are examined.

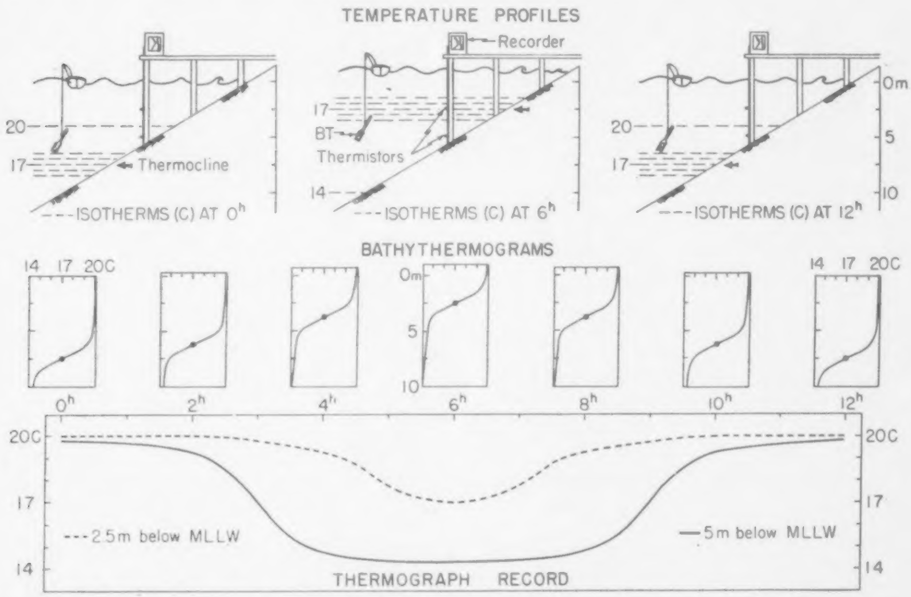

Fig. 3. Schematic model of temperature variation as shown by isotherms in profile normal to shore (top row), by BT traces from lowerings at fixed location at two-hour intervals (middle row), and by oscillation in thermograph traces from temperature-sensitive elements, e.g., *thermistors*, at fixed depths on pier pile (bottom row).

Bathythermograms. Lowering a BT produces a trace of temperature against pressure (depth), a bathythermogram. Suppose the vertical movement of the isotherms in the section is sinusoidal with respect to time. The vertical movement in the model is shown by a series of bathythermograms (Fig. 3, middle row) such as would be obtained by lowering a BT every two hours at the location indicated in the section. The depth of the thermocline is marked by a black dot on each trace and the dots lie on a sine curve under the assumptions made. The depth scale is fixed relative to mean lower low water (MLLW) rather than relative to the surface as on an actual BT grid.

Thermograph Record. A record of temperature against time such as would be obtained from temperature-sensitive elements, e.g., *thermistors*, mounted on a pier pile is also

shown in Fig. 3 (bottom). The model thermogram indicates the temperature oscilations obtained from thermistors at two different depths as a result of the vertical movement of the isotherms. The shape of the temperature-time curves is of interest. It is clear that the slope of each curve depends upon both the vertical temperature gradient and the rate of vertical movement of the isotherms. Although the isotherms are assumed to move sinusoidally, the presence of a strong gradient in the thermocline layer causes marked deviation from the sinusoidal shape in the thermograph records. More than 75% of the temperature decrease or increase takes place within two hours.

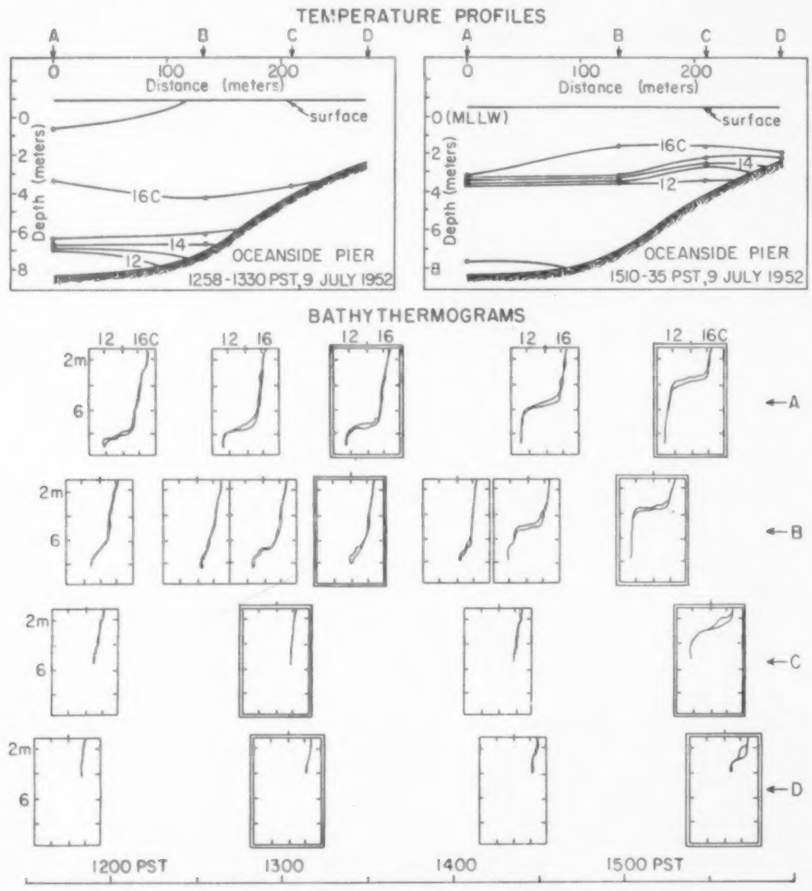

Fig. 4. Observed temperature variation along Oceanside Pier. Tracings of BT slides arranged vertically by station location A-D and centered horizontally according to time of lowering. Profiles at two different times constructed from tracings with double border. Surface level represents stage of tide.

A sufficiently steep temperature gradient in the thermocline layer, relative to the layers above and below, would produce thermogram curves of much greater distortion with the major part of the temperature change occurring in a fraction of an hour. The time at which the maximum change is recorded depends upon the depth of the thermistor and differs by more than an hour in the two model curves. The model

has been simplified by assuming horizontal isotherms. If the isotherms are sloped and move horizontally as well as vertically, the shapes of temperature-time curves will be additionally affected. Time changes in the vertical temperature gradient will likewise affect the shapes of the curves.

OBSERVATIONS

The schematic model described above is oversimplified. However, it provides a useful framework for a description of variations in the temperature field as shown by observations. A brief description of instruments used and results obtained follows.

Instrumentation. The bathythermographs used had been modified to produce full travel of the smoked-glass slide at a depth of 15 m. The double traces which occur in some cases are believed to be the result of real changes in the temperature-depth curve. The slides were processed and photographic prints made by the standard method (LAFOND, 1951).

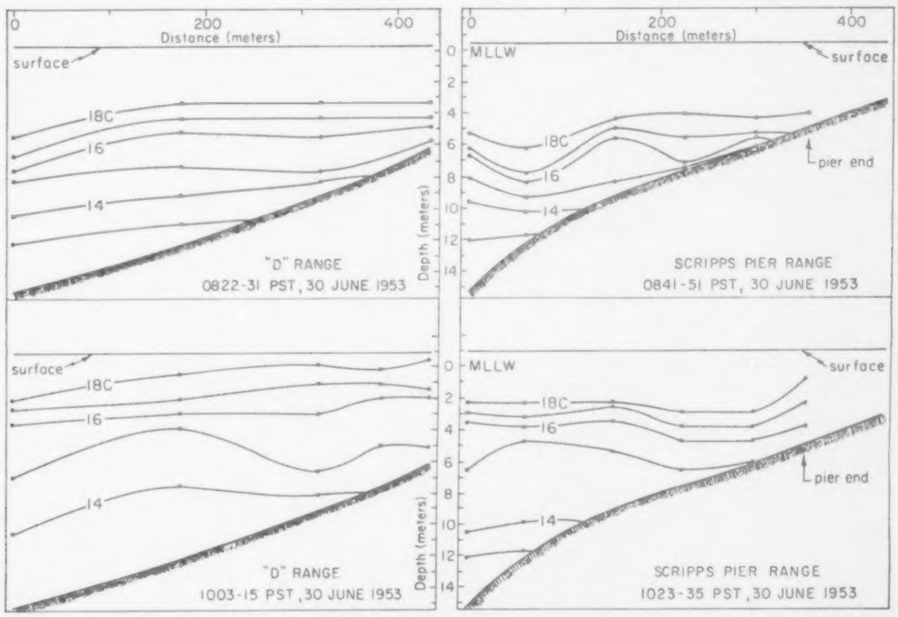

Fig. 5. Temperature profiles at two different times along two parallel ranges in Scripps area (range locations in Fig. 6). Plotted points from BT traces.

Electrical resistance thermometers with the temperature-sensitive elements mounted at the ends of water-tight conducting cables have also been employed. When these "casting" thermometers are used, the depth of the element is obtained by noting the length of cable paid out at the time of reading.

Continuous records of the temperature at two depths near the end of Scripps Pier and Oceanside Pier were made from thermistor elements. At La Jolla the thermistors were mounted on a pier pile at depths of 1·3 m and 4·5 m below MLLW and at Oceanside at depths of 1·5 m and 5·3 m. The lower thermistor was within 1 m of the bottom at La Jolla and about 3 m above bottom at Oceanside. Each

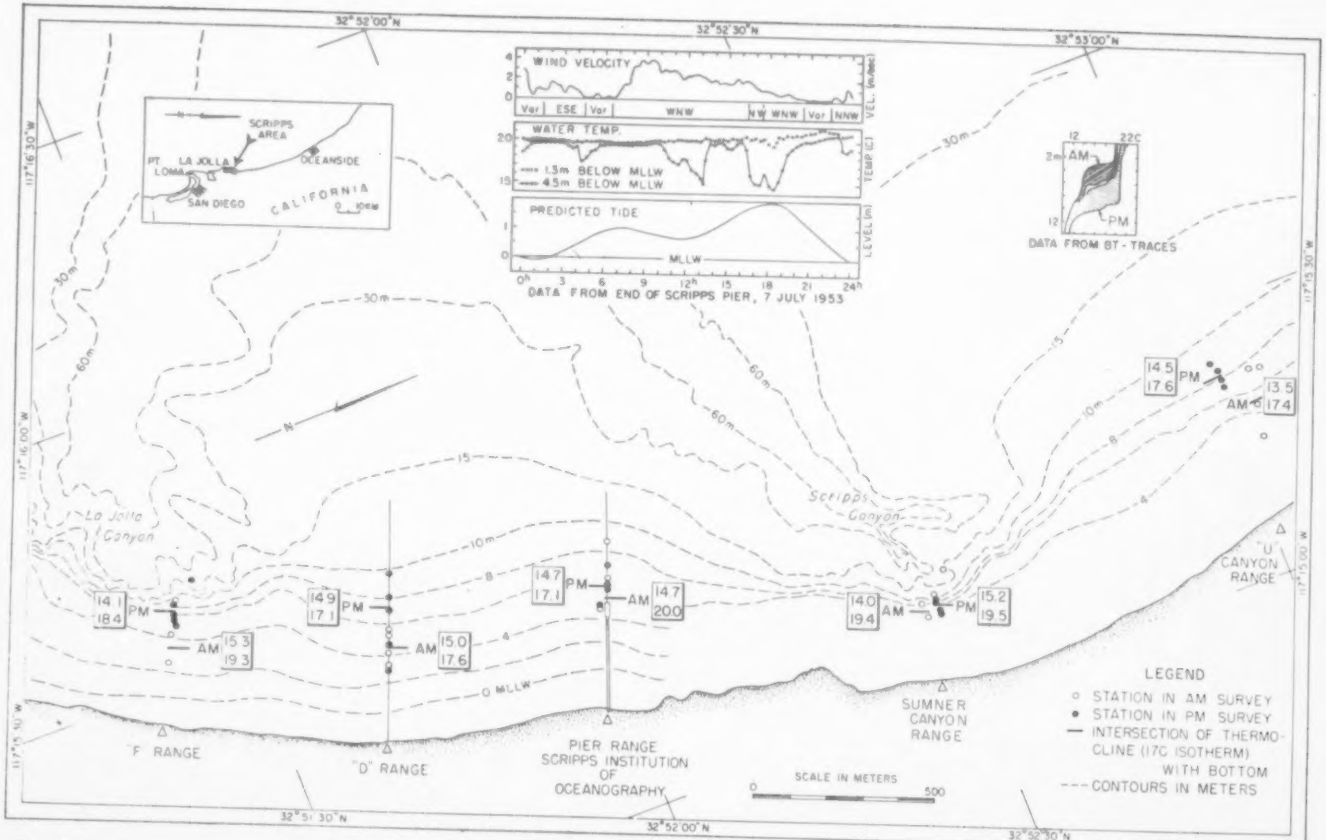

Fig. 6. Location of intersection of thermocline with bottom in Scripps area in AM (0932-1103PST) and PM (1338-1507PST) surveys on 7 July 1953. Numbers in boxes show temperature (C) of bottom water at stations immediately seaward and shoreward of intersection. Insets: location map (left); wind, water temperature, and tide at pier end (center); comparison of BT-grid areas covered by AM and PM traces (right).

of the two signals at La Jolla was fed into a separate channel of a 12-channel Speedomax (*Leeds and Northrup Co.*) and was printed every 38·7 sec ; the Speedomax used at Oceanside was a single-channel, pen-type and the signal from the upper thermistor was programmed to record for ten minutes out of each hour.

For the purposes of the present study it is sufficient to know the temperature to an accuracy of $\pm$ 0·2 C and all instruments were so calibrated. Except for one of the casting thermometers, the instruments are capable of greater accuracy and differences between readings may be trusted to within $\pm$ 0·1 C.

Temperature Profiles. BT lowerings were made at four positions along Oceanside Pier, and depths of whole number values of temperature were read from the right-hand traces of the resulting bathythermograms. Fig. 4 shows the isotherms interpolated between the four positions for two sets of observations. About one-half hour was required to make each set of lowerings and the time interval between profiles is between two and three hours. BT lowerings were made on two other days, and results were similar, i.e., vertical movement of isotherms was noted.

Fig. 5 shows temperature profiles along the Pier Range and " D " Range, Scripps area (Fig. 6 shows range locations). The time separation is about two hours, and around ten minutes were required to make the BT lowerings and run each range with the amphibious craft (DUKW). Positions along the range were determined by sextant angles. Additional profiles were made on two other days along the ranges and on three different days along Scripps Pier itself. Results were similar to those presented.

Intersection of the Thermocline with the Bottom. The inshore-offshore movement of the intersection of the thermocline with the bottom was determined in the Scripps area along a section of shore between 3 and 4 km long. Stations along or in the vicinity of five different ranges (Fig. 6) were occupied by the DUKW, and the temperature of the water immediately above the bottom was measured with a casting thermometer. As before, positions were determined by sextant angles, and the depths were noted as an added check on position and inshore-offshore movement between the morning (0932-1103 PST) and afternoon (1338-1507 PST) surveys. The 17 C isotherm was taken to represent the thermocline and its intersection was interpolated between the observed values of bottom temperature. The change in thermal structure is indicated by an inset in Fig. 6 which shows the BT-grid areas encompassing all morning (AM) and all afternoon (PM) traces from a total of 16 bathythermograms taken during the two surveys.

For reference, information is presented from records of wind and temperature near the end of Scripps Pier. Values of wind velocity and of temperature have been read at 20-min intervals and connected by a smooth curve (Fig. 6, inset). The dominant wind direction is included and also the predicted tide (U.S. Coast and Geodetic Survey, 1952). In general, observed tide level is within 10 cm of the predicted value at Scripps Pier.

Thermograms, Wind and Tide. Values of temperature on the hour and half-hour have been read for an eight-day period from records from three of the four thermistors. Only hourly readings could be made from the programmed thermogram for the 1·5 m depth at Oceanside. The successive values, which were read to the nearest quarter degree centigrade, were plotted and joined by straight lines (Fig. 7). This procedure is necessary to condense the thermograms so that comparisons and

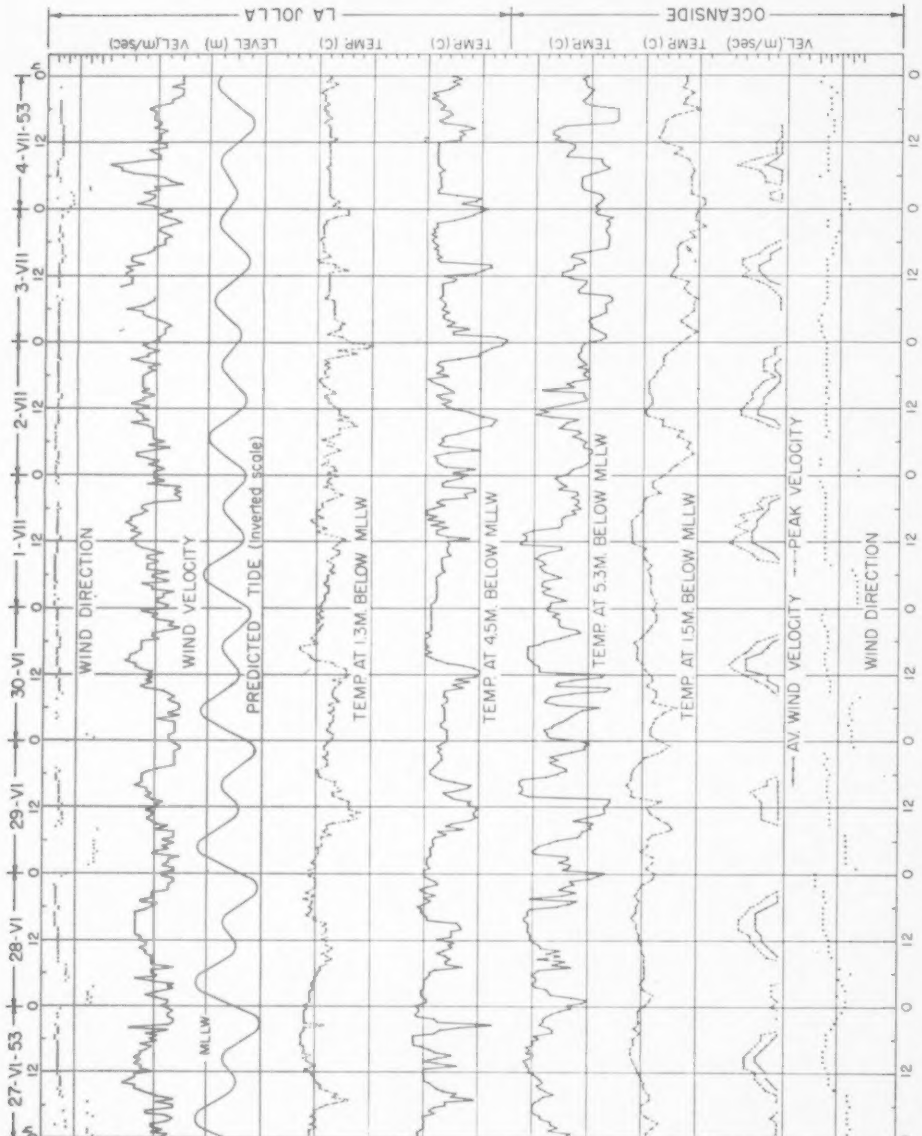

Fig. 7. Smooth temperature oscillations at two depths from pier ends at La Jolla and Oceanside, California, from 27 June through 4 July 1953. Variation in wind and tide also shown for comparison.

reproductions may be made. The degree of smoothing for an extreme case may be judged from examination of a tracing of the Oceanside thermogram for a six-hour period on 30 June 1953 (Fig. 8).

Oscillations in temperature as large as those shown in Fig. 7 have occurred during some periods in the summer and fall of 1953. The six-hour interval in Fig. 8 was specifically chosen because it represents an extreme in the magnitude of shorter-time fluctuations during the whole eight days.

For comparison with temperature, the wind and tide are also shown on Fig. 7. Wind records from a Friez Aerovane at the end of Scripps Pier have been read at half-hour intervals. The direction from which the wind blew was read to the nearest

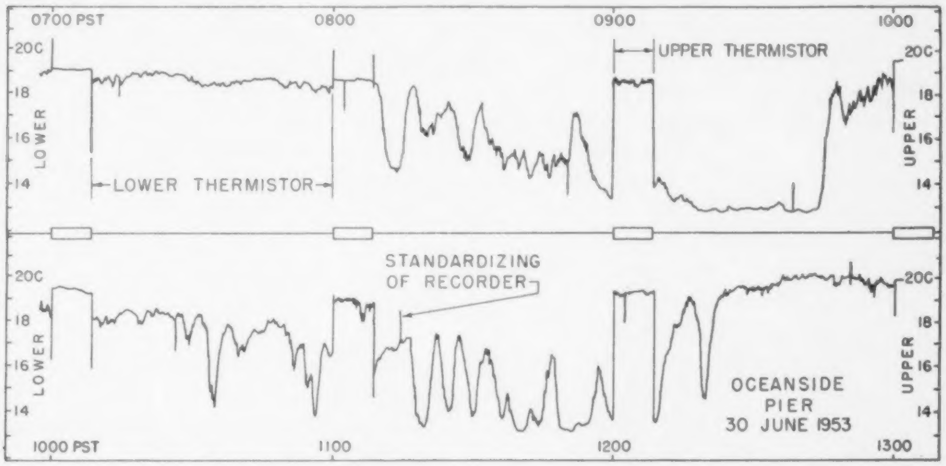

Fig. 8. Reduced tracing of programmed thermogram from Oceanside Pier for 0700-1300, 30 June 1953. Boxes on centerline of diagram indicate first 10 min of each hour when trace is from upper thermistor (1·5 m below MLLW). Remainder of time trace is from lower thermistor (5·3 m below MLLW). Temperature scales differ slightly because of non-linearity of thermistors. Sharp, vertical lines in trace are caused by programming and standardizing mechanisms.

of 16 points of the compass when the velocity was greater than 1 m/sec. The predicted tide for Scripps Pier is shown on an inverted scale and the same curve applies to Oceanside. Wind data for Oceanside are taken from records at the Camp Pendleton boat basin, 3 km north of the Oceanside Pier. Hourly averages and peak velocities above 2·5 m/sec have been plotted along with direction to the nearest of 16 compass points.

DISCUSSION

The Nature of the Temperature Oscillations. The model involves the simple and obvious proposition that oscillations in the thermogram traces are associated with vertical movement of isothermal surfaces. The reproduced data, particularly the profiles, support the proposal. Additional profiles, not reproduced, are in agreement.

However, as previously stated, the shape of the thermogram curves depends not only upon the rate of rise or fall of isotherms but also upon their vertical spacing. Fig. 7 shows that traces from thermistors at different depths exhibit differences in amount and rate of temperature change. Temperature changes from thermistors

near the surface are often small relative to changes from thermistors near the thermocline.

Local temperature changes may be caused by local heating or cooling or by horizontal and vertical water movement. As LEIPPER (1950) has pointed out, gain or loss of heat through the surface cannot account for the temperature oscillations recorded from deeper thermistors. A day-night range of less than 2 C in the upper few meters is the most that can be expected. The observed oscillations must be accompanied by water movement and, consequently, the proposed model is incomplete dynamically. With regard to water movement, an examination of the data shows first that the isotherms are not simply following the rise and fall of the sea surface under the influence of ordinary tides. Secondly, the profiles show that different isotherms may have differing magnitudes of rise or fall. The 13 C and 14 C isotherms on the Pier Range profile in Fig. 5 show much less change than other isotherms. It is concluded that the water movement *may* vary with depth.

As proposed in the model, the profiles and Fig. 6 indicate that the intersection of the thermocline with the sloping bottom does move toward or away from shore. The observed isotherms are not everywhere horizontal but show appreciable slope both normal and parallel to shore.

The observations reproduced are confined to an area between the surf zone and the 15 m contour. At any instant, the surf zone is generally well stirred and isothermal, but it experiences temperature variations similar to those of water near the surface at the pier ends. There is evidence that temperature oscillations extend far seaward of the reproduced sections. Unpublished bathythermograms taken by HUBBS and others to a distance of 2 km from shore in the Scripps area show pronounced vertical movement of isotherms at all stations during a time interval of more than 24 hr. LEIPPER (1950) comments on the variation in depth of the thermocline observed on 15-16 September 1948 at Scripps Pier and at two ships located approximately 33 km west-northwest and northwest of the Scripps Pier, respectively. Profiles reported by RAWN, *et al.* (1952) from the Oceanside area show that the oscillations extended at least 4 km from shore in that area during one 24-hr interval. Profiles off Point Loma (RAWN, *et al.*, 1952) and temperature variations recorded by UFFORD (1947) show the phenomenon extending south of La Jolla.

The profiles and thermograms show that the temperature oscillations at Scripps and Oceanside have a similar character in spite of the great difference in bottom topography. There is no obvious, persistent coherence in the thermograms from these two locations over 40 km apart (Fig. 7). On the other hand, there is evidence of coherence on one occasion over a distance of less than 4 km (Fig. 6).

Periodicities. A description of the thermogram data is incomplete without mention of periodicities. Rhythmic phenomena which might produce oscillations in temperature are the diurnal wind and the tides. The wind has the character of a land and sea breeze and the tides are of the mixed type, showing considerable diurnal inequality (Figs. 6 and 7).

The thermogram curves have a rather high degree of irregularity in general appearance. However, if curves of wind and temperature or tide and temperature and compared (Fig. 7), one gets the impression that good correlation exists *in some sections of the records.* Good correlation in a particular interval of time may result from chance as COLE (1951) has so convincingly demonstrated in a comparison

of curves derived from Douglas fir growth and random sampling numbers from Tippet.

As Leipper states the temperature dips may be associated with any stage of the tide. However, he reports that of the total number of distinct dips occurring in several hundred days 55 per cent came within two hours of high tide while only 24 per cent came within two hours of low tide. Defant (1950b) has subjected a four-day thermograph recording from Scripps Pier to harmonic analysis and concludes (p. 125) :

> " The tidal influence is very pronounced. The tide and temperature curves are almost completely reversed, and the phase differs by half a period. The variation in temperature with semidiurnal tide in the surface and bottom layers attains an amplitude [double] of more than 3°C ; with the diurnal wave in the surface layer it attains a magnitude of only 1°C."

Defant (1950a, b) has suggested that internal waves of tidal period, i.e., internal tides, are widespread in the oceans and he includes the above analysis as part of the evidence. There remains a question of significance (Haurwitz, 1952) and the length of record examined is important. In the Scripps thermogram for 4·5 m (Fig. 7) the correlation between inverted tide and temperature is obviously good on July 3 and 4, as it was in the record analyzed by Defant. However, there is not such an obvious correlation on the other six days. It is, therefore, concluded that while thermograms suggest the possibility of oscillations of tidal period, the oscillations in no way show the persistent regularity demonstrated for surface tides.

Isotherms in the sea may have a vertical oscillation of tidal period which is more persistent than shown by the thermograms. The amplitudes of trace oscillations depend critically upon the relative depth of thermistor and thermocline. Since the mean depth of thermocline may change after several days, the interpretation of a long thermogram is difficult. Data on the actual vertical movements of isotherms are needed and could be obtained by programmed recordings from thermistors closely spaced along a vertical cable. It is hoped that several such internal-tide gauges can be operated from the ends of piers in the future. Since temperature " noise " is present, some filtering of the records will undoubtedly be desirable and, then, analyses for periodicities and significance tests can be made.

Internal Waves. Temperature oscillations of the type shown by the data, but from observations in deeper water, have been attributed to internal waves and internal tide (e.g., see Sverdrup, Johnson and Fleming, 1942 and LaFond, 1949). An internal-wave mechanism is in complete agreement with profiles and other data from Oceanside as well as Scripps. However, observations of the motion are necessary to confirm the presence of internal waves and these have not been made.

Ufford (1947) has demonstrated the existence of internal waves of periods from 9 to 136 minutes in the San Diego area and has remarked on the existence of waves of tidal period which show prominently in his temperature data. Ewing (1950) has shown a relationship between band slicks on the surface and refracted internal waves in the San Diego and La Jolla areas, and both he and Ufford find internal waves which progress toward shore.

Since many oscillations in the thermogram traces quite possibly result from internal waves, speculation on the behaviour of internal waves in shallow water may be of interest. In addition to refraction, shoaling water may cause reflection and possibly

standing waves, or internal breaking and surf (DEFANT, 1950a) may result. From KEULEGAN'S (1953) theoretical investigation of internal solitary waves one might expect that internal troughs as well as internal crests could reach instability and break in shoaling water.

Measurements of temperature with depth have occasionally shown inversions which would be expected with internal surf. Pertinent in this regard are observations of a narrow zone of debris, kelp, foam, and jellyfish with associated band slicks which approached Scripps Pier on 12 June 1953. The debris zone extended generally parallel to shore but was curved inward toward shore over both submarine canyons. The temperature at the pier end was 17·1 C at surface and 12·7 C at bottom with the thermocline located at 2 to 3 m below surface. As the debris zone approached the pier end the thermocline moved downward and within 15 min after the zone had passed the pier end the bottom temperature was 16·8 C. However, water 3 m above bottom was 0·3 C colder than water at the bottom. The tide was ebbing during the observations and the wind record was very similar to that of 30 June 1953 (Fig. 7).

The observed movement of the debris zone may indicate a shoreward movement of warm surface water accompanied by convergence and sinking. Continuity requires a corresponding seaward movement of deeper, cold water. Temperature observations are consistent with such an interpretation of the motion and suggest the approach toward shore of a steep, or breaking, leading edge of an internal trough. The orientation of debris zone and slicks indicates refraction by the canyons.

The velocity of an internal solitary trough is 15 cm/sec if calculated from Keulegan's formula (1953, eq. 88) for a two-layer system with upper layer of thickness 3 m, lower layer 5 m, density difference of 0·001 gm/cm^3, and trough with height 2 m. On the basis of visual estimates of distances at various times, the observed speed of the debris zone was about 10 cm/sec. The water velocity should be less than or equal to the internal trough velocity. However, both estimates are very approximate, and a comparison simply shows that the observations *may* indicate an internal wave mechanism.

If the temperature oscillations are associated with internal waves, the problem of the cause of the waves still remains. Tide (DEFANT, 1950a ; HAURWITZ, 1950) and wind are probably important, but the data as presently analyzed offer little more than a basis for speculation. RUDNICK and COCHRANE (1951) suggest that the generation of internal tide at ocean boundaries seems a very probable process. In this regard, the thermograms show that there may not be a constant phase coupling between internal and surface tides in very shallow water.

Advection and Stirring. LEIPPER (1950) proposes as an explanation that temperature variations at Scripps Pier may be caused by stirring of shallow stratified water and subsequent oscillating movements associated with tidal currents. He suggests that the irregular bottom topography causes horizontal differences in tidal current in certain regions. The differences, in turn, lead to the formation of eddies which bring about stirring and cooling in the surface layers. Oscillating tidal currents then cause the " cold spot " so formed to migrate back and forth.

The relatively regular topography in the Oceanside area (Fig. 2) makes it unlikely that differential tidal stirring exists there on a scale comparable to that suggested by LEIPPER for the Scripps area. Different explanations may be required for the two

areas, but the similarity in observed temperature oscillations make a common explanation such as an internal-wave mechanism attractive.

However, the present data do not rule out the possibility of advection and stirring being factors in producing oscillations. For example, if the isothermal surfaces are for any reason sloped in a direction parallel to shore and there is a current component parallel to shore, temperature variations will be recorded at a fixed locality. Some stirring must accompany internal waves, particularly in shallow water. Coastal currents, wind stirring, and surf stirring are perhaps all factors which affect the very shallow summer thermocline in the nearshore region. Time and space variations in these factors exist and may certainly cause some temperature variation.

Advection and stirring associated with transient rip currents have been observed to produce temperature variations of as much as 1 C or 2 C at the end of Scripps Pier.

It is, of course, well established that advection and stirring by winds produce longer-term changes in temperature, e.g., as a result of upwelling (Sverdrup, Johnson, and Fleming, 1942) or sinking (Longard and Banks, 1952).

Applications. The temperature oscillations represent changes in the nearshore environment which are of interest in marine biology. Benthic forms at depths ranging from about 3 m to at least 8 m may experience abrupt changes in temperature during a single summer day which are as great as the seasonal changes. The 0800 temperature of bottom water at Scripps Pier for the coldest month, February, averaged over the years 1925-1951, is 13·8 C and for the warmest month, August, 18·8 C. This seasonal change of 5 C was equalled on four out of the eight days from 27 June to 4 July 1953 (Fig. 7), and at four different times the temperature near the bottom dropped to 14 C or lower. Such changes are frequent rather than rare. Even in August the temperature dips reach 15 C or lower.

The vertical movement of isotherms causes changes in the thickness of the isothermal layer above the thermocline. The changes extend out 2 km or more from shore. Refraction of horizontally propagated underwater sound, which is critically dependent upon the temperature field, will be affected by the observed changes. In this area salinity changes are small enough to be ignored in comparison with temperature changes in calculating sound velocity. The temperature oscillations are associated with density oscillations of importance.

Horizontal and vertical movements of water are associated with the temperature oscillations. At least in part the horizontal movement is onshore and offshore, probably in the nature of an internal wave. Estimates show velocities greater than the onshore-offshore movement from surface tide. This motion should be considered in work on movement of suspended sediment.

Some vertical stirring and mixing undoubtedly accompanies the oscillations. If internal waves become unstable and break, the stirring may appreciably reduce the nearshore temperature in the sense described by Cooper (1947).

The observations suggest the existence of internal tide, but more suitable data are needed for analysis. Piers on exposed coasts constitute a bridge over the surf zone and are more economical bases for long-term operation of internal-tide gauges than anchored ships. It is suggested that such facilities be exploited more. Undoubtedly, comparisons with at least limited observations from deep anchor stations will be desirable and necessary to establish fully the nature of internal tide.

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University of California, Scripps Institution of Oceanography, La Jolla, California, U.S.A.

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Reconnaissance survey of the abyssal plain south of Newfoundland

BRUCE C. HEEZEN, MAURICE EWING and D. B. ERICSON

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Summary—This paper presents a new chart of the abyssal plain south of Newfoundland, contoured in 5-fathom intervals, based on a survey with a newly developed precision depth recorder. The area is of interest in connection with the 1929 Grand Banks earthquake.

The abyssal plains are flat, nearly level areas which occupy the deepest portions of many of the ocean basins. The development of a precision depth recorder with an accuracy better than $\pm$ 1 fathom was required before an effective study of the abyssal plains could be made. In 1953 a reconnaissance survey was run with such a recorder on the abyssal plain south of Newfoundland. The gradient of the plain decreases from 1 : 1,000 at its northern margin near 41°N to 1 : 5,000 near latitude 32°N. South of 32°N the gradient probably flattens still more before the southern margin of the plain is reached. The plains have been interpreted by various writers as : (1) atectonic areas ; (2) subaerial erosion surfaces ; (3) lava plains ; (4) areas of long continued sedimentation ; (5) surfaces produced by the spreading of extremely fine sediments by bottom currents ; (6) areas in which the original relief has been buried by the deposit of turbidity currents. Every core obtained from the abyssal plains to date contains evidence of turbidity currents either in the form of graded bedding, shallow water foraminifera or excessively high calcium carbonate content. The plains slope away from areas adjacent to sediment sources. The present writers consider it likely that all abyssal plains represent areas in which most of the original relief is buried beneath the deposits of turbidity currents. Only the partly buried isolated hills and seamounts which rise from the abyssal plain remain of the original topography. Continued turbidity current transport of material into the basins continually extends the abyssal plains.

INTRODUCTION

ONE of the most striking discoveries of the 1947 Mid-Atlantic Ridge Expedition was that vast areas of the deep ocean floor of the North Atlantic are occupied by flat, nearly level plains (TOLSTOY and EWING, 1949). In 1948 the Swedish Deep Sea Expedition discovered similar plains in the Indian Ocean south of the Bay of Bengal (PETTERSSON 1953 ; KOCZY 1954). On the 1950-52 *Challenger* Expedition a further study was made of the Indian Ocean plain (GASKELL and ASHTON, 1954). The abyssal plains of the North Atlantic have been delineated by a score of tracks made by the R/V *Atlantis* between 1947 and 1952, using a NMC-1 echo sounder (Fig. 3). Although a fair idea of the extent of the abyssal plains can be obtained from a study of records made by the standard echo sounders, the gradients and small scale irregularities are obscured by the large errors inherent in these instruments. It became obvious that a much more accurate echo sounder recorder was needed before an effective study of the abyssal plains could be made. To fill this specific need a precision depth recorder was developed (LUSKIN, HEEZEN, EWING and LANDISMAN, 1954) during the spring of 1953.

GENERAL DESCRIPTION *VEMA* CRUISE #2

The Research Vessel *Vema* sailed on her second scientific cruise with the primary purpose of running a reconnaissance survey of the abyssal plains north and east

of the Bermuda Rise. In addition to precision depth measurements other scientific programmes included seismic reflection measurements, total magnetic intensity measurements and biological and geochemical sampling (Fig. 2). Only the topographic results are to be presented here.

The first week of the cruise was devoted to a study of the continental slope and continental rise south of Cabot Strait and will be reported on elsewhere.

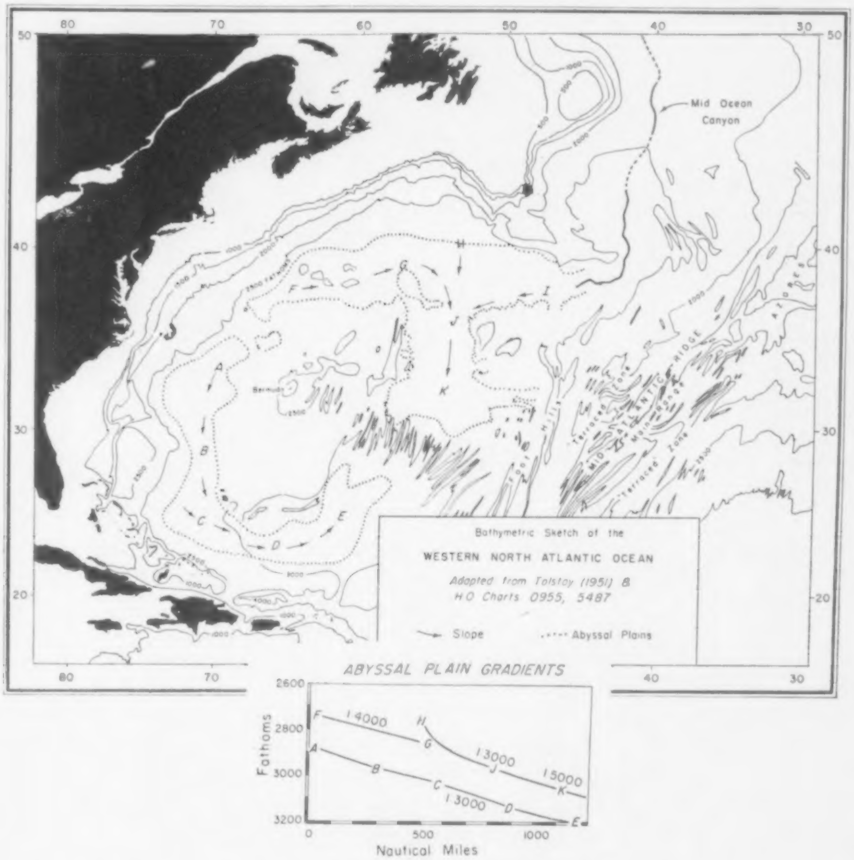


Fig. 1. Abyssal plains of the North Atlantic.

THE ABYSSAL PLAINS

General

An abyssal plain is an area of the deep ocean floor in which the ocean bottom is flat and the slope of the bottom is less than 1 : 1,000. Abyssal plains are known to be present in the Indian Ocean south of the Bay of Bengal, in the equatorial Atlantic on either side of the Mid-Atlantic Ridge, in the Canary Basin of the eastern Atlantic, in the Gulf of Mexico, the Yucatan Basin, the Caribbean Sea, the eastern Old Bahama Channel, and in the western North Atlantic. No doubt many more plains will be discovered when more precision depth recorder profiles are run across poorly sounded deep ocean areas.

The abyssal plains of the western North Atlantic belong to two systems, one south and west of the Bermuda Rise and one north and east of the Bermuda Rise (Fig. 1). The southern plain slopes southward from a point west of Bermuda to about Lat. 25°N where the slope changes to east. The deepest portion of the plain is reached near Long. 60°W. The northern plain appears to have two branches. One begins near the mouth of the Hudson Canyon at Lat. 35°N, Long. 70°W and slopes east toward

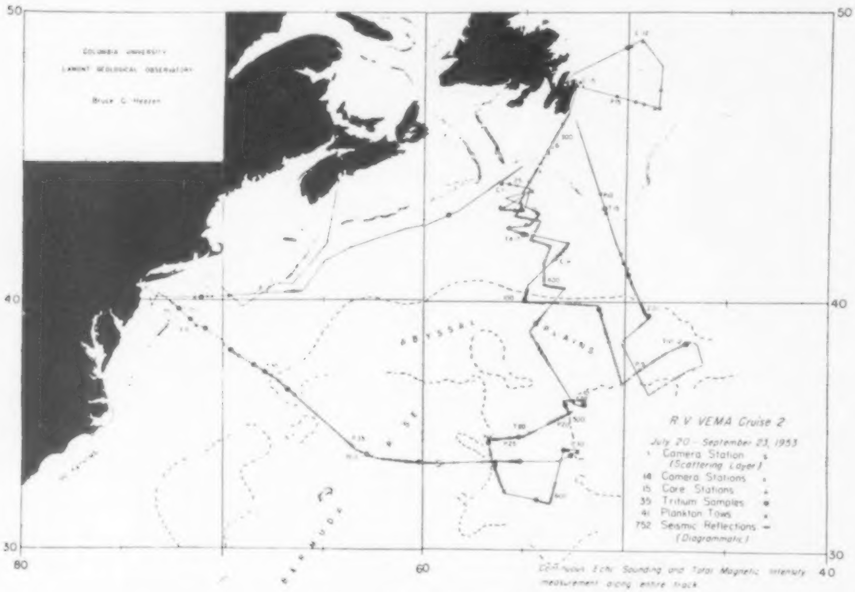


Fig. 2. Track Chart – *Vema* Cruise #2.

Long. 55°W. Another begins near the locality where the Northwest Atlantic Mid-Ocean Canyon (EWING *et al.*, 1953) cuts through the southeast Newfoundland Ridge (38°N Lat., 45 W Long.) and slopes west toward Long. 55°W. Near 35°N 53°W the two branches join and the slope of the plain changes to south. South of about 29°N the plain apparently ceases to exist, being completely broken up by hills. It is not known if the northern and southern plains are connected by canyons running between Lat. 29°N and Lat. 27°N, or if the two are completely separated by a mountain barrier (HEEZEN, EWING and ERICSON, 1951).

The VEMA #2 Topographic Survey of the Abyssal Plain (1953)

The 1953 *Vema* (Cruise #2) survey of the abyssal plain south of Newfoundland was made possible by the development of the precision depth recorder (LUSKIN, HEEZEN, EWING and LANDISMAN, 1954) which records depth to an accuracy of better than 1 fathom in 3,000. From the precision depth recorder records made on *Vema* Cruise #2 a preliminary chart (Fig. 3) with a 5 fathom contour interval has been prepared of a 150,000-square mile area of the abyssal plain south of Newfoundland. With standard sounders which usually have errors of $\pm$ 25-50 fms. in 3,000 fms. and often have errors of $\pm$ 100 fms. in 3,000 fms. a realistic chart of this area could

not have been prepared at all. Since the chart was prepared on the basis of only 8 profiles across the abyssal plain details will no doubt gradually change as more facts are accumulated.

The area studied on *Vema* Cruise #2 lies in the centre of the abyssal plain northeast and east of the Bermuda Rise (Fig. 3). The studied area extends from the continental rise south of Newfoundland south to Lat. 32°N and from the eastern margin of the Bermuda Rise to the western margin of the Mid-Atlantic Ridge.

The gradient of the abyssal plain between Lat. 32°N and 33°N is 1 : 5,000. South of Lat. 32°N the slope probably flattens and may be virtually zero near the southern margin of the plain. North of Lat. 32°N, the gradient gradually increases (Fig. 4). At 37°N the gradient is 1 : 3,000, and at 38°N 1 : 2,000. At the transition between the abyssal plain and the continental rise south of Newfoundland (Lat. 41°N) the gradient increases to more than 1 : 1,000.

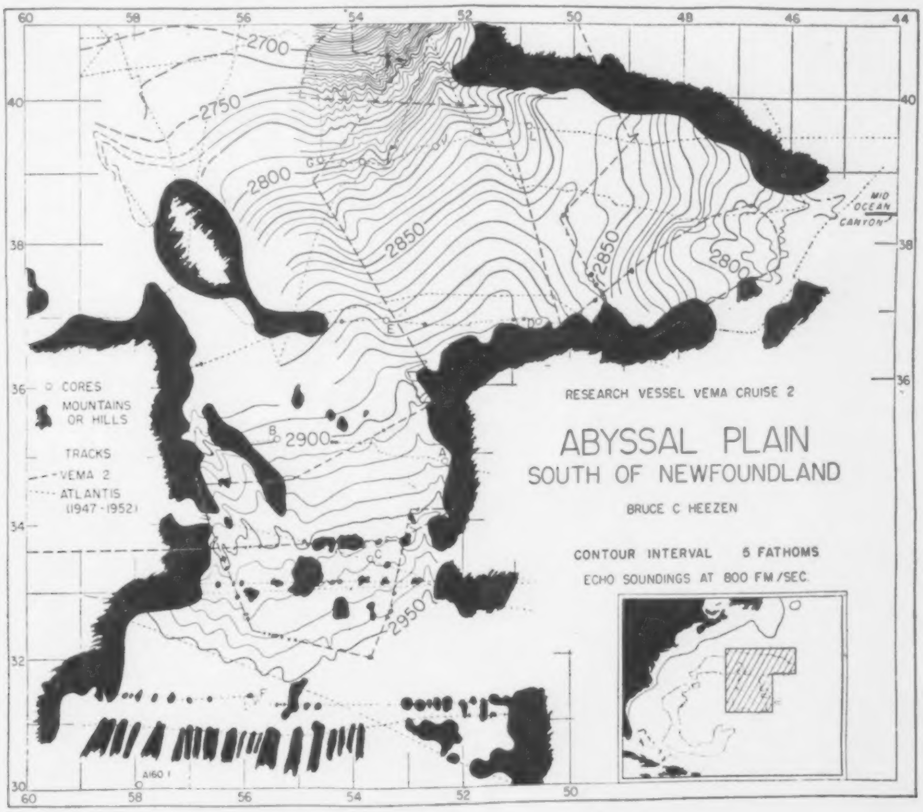


Fig. 3. Chart of the abyssal plains south of Newfoundland.

The boundaries of the abyssal plains are very abrupt in many places and very gradual in others, apparently falling into two distinct categories. The gradual transitions are at the base of the continental rise. However, the continental rise-abyssal plain boundary is at times very sharp, as in the case of the south east edge of the Grand Banks. The sharpest boundaries of the abyssal plains occurs at oceanic rises and

seamounts. For example, the southern part of the abyssal plain shows abrupt boundaries on the west with the Bermuda Rise and on the east with the Mid-Atlantic Ridge (Fig. 5). When running profiles across the margin of the plain into the Bermuda Rise or into the foothills of the Mid-Atlantic Ridge spots are often found where the depth exceeds that of the adjacent plains. In some areas large lobate flat-floored

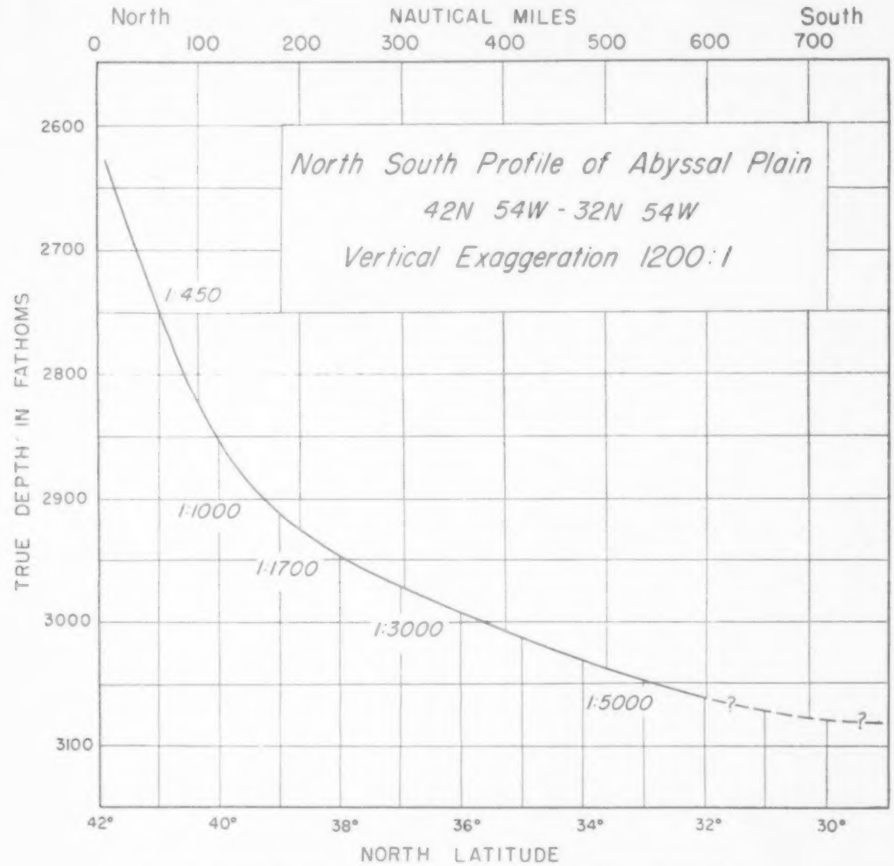


Fig. 4. North-South profile along Long. 54 from 32 to 42 North Lat.

valleys extend from the abyssal plain into the mountain areas. One such valley runs northwest from Lat. 34°N Long., 57°W (Fig. 3). The southern margin of the plain is formed by a saw-tooth pattern of hills and flat-floored valleys. Further south the valleys narrow, deepen and lose their flat-floors and in this way the abyssal plain feathers out.

Seamounts protruding from the plain are virtually absent north of Lat. 36°N, but south of Lat. 36°N they appear to increase in number until the southern margin of the plain is reached. There is some indication that the number of seamounts may decrease between 31°30′N and 32°30′N where the plain widens eastwards and westward. From the point where the Mid-Ocean Canyon cuts through the southeast Newfoundland Ridge to Long. 50°W the slope of the plain is west-northwest. This

portion of the plain is not as smooth as the portion south of Lat. 36°N (Fig. 3). A local deep area lies at the southern flank of the southeast Newfoundland Ridge between Long. 48°W and Long. 51°W. This deeper area is joined to the southern parts of the plain by a saddle which runs from 34°N 50°W to 37°N 51°W.

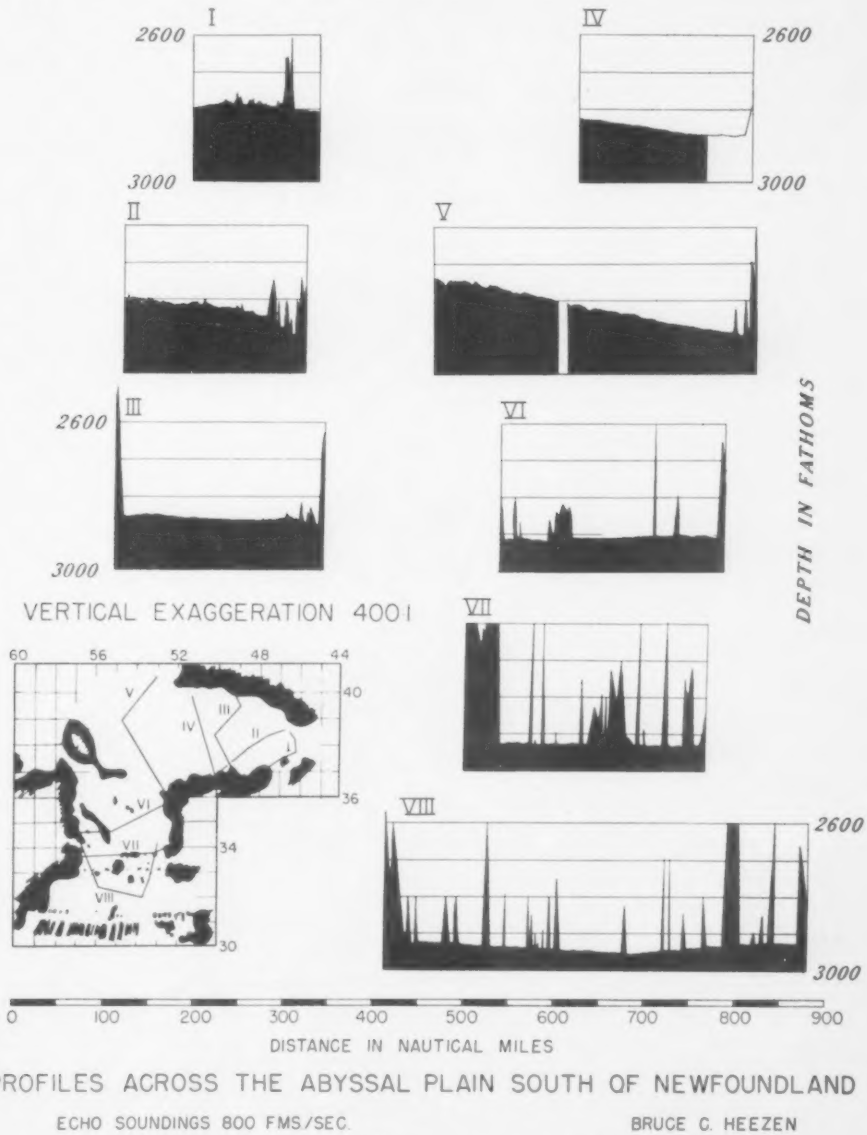
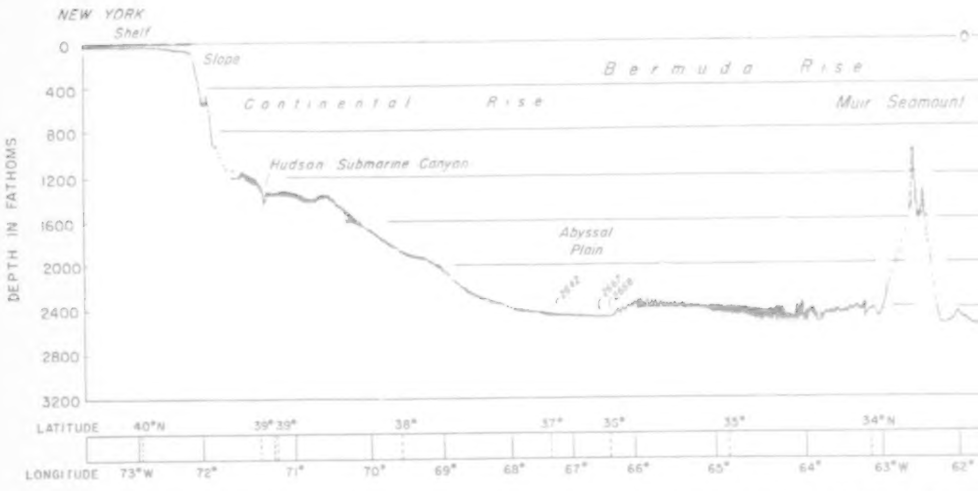


Fig. 5. Profiles across the abyssal plains.

Sediment Cores

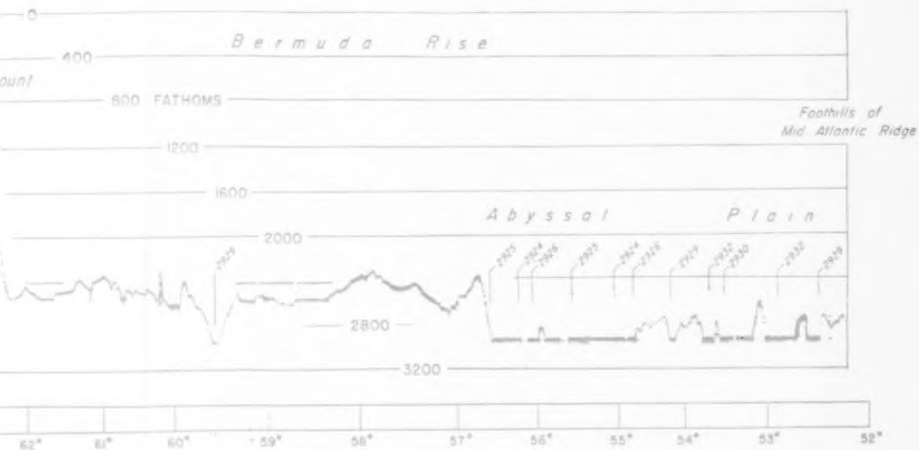
The contrast between abyssal plain and the adjacent rises is equally sharp where sediment types are considered. Between 1948 and 1952 the R/V *Atlantis*



PRECISION DEPTH RECO

Western Mid Atlantic Ridg

Fig. 6. Precision depth recorder profile between the V



RECORDER PROFILE

Ridge to New York

the Western Mid Atlantic Ridge and New York.

2

occupied twelve sediment core stations (Fig. 3) in the abyssal plain northwest of the Bermuda Rise (ERICSON, EWING and HEEZEN, 1951 ; HEEZEN, ERICSON and

Table I

Cores from the Abyssal Plain South of Newfoundland, 1948-1952.

No.	*N. Lat.*	*W. Long.*	*Fms. Depth*	*Core Lgth. Meters*
(A) A152-131	34°52′	52°20′	2900	Neg.
	No core recovered, coring tube bent.			
(B) A152-132	34°14′	55°23′	2900	Neg.
	No core recovered, coring tube bent.			
(C) A153-141	33°26′	53°48′	2925	10·25
	Red clay of normal deep-sea facies extends to 30 cm, below which is a series of alternating layers of red clay, gray clay, and quartz silt to 400 cm. From 400 to 600 cm. there is micaceous glauconitic sand. At 460 cm the sand has a median diameter of 110 microns and is well sorted, having a quartile deviation of 0·7. Between 600 and 718 cm there is a series of brown clay layers alternating with silt and sand. From 718 cm to the bottom of the core there is again glauconitic sand, which has at 790 cm a median diameter of 103 microns and is also well sorted, having quartile deviation of 0·8. The lower sand layer shows a gradual increase in particle size downward. Both sand layers contain a few foraminifera among which are the shallow water benthic forms Elphidium incertum var. clavatum, Elphidiella arctica, and Nonion labradoricum.			
(D) A157-17	36°56′	50°40′	2905	·20
	Red clay was recovered in the top of the core below which the pipe was empty – the lower portion of the core presumably ran out.			
(E) A157-18	36°55′	53°26′	2900	·20
	Red clay over silt below which the pipe was empty, presumably portion of the core ran out.			
(F) A160-16	31°19′	55°48′	2945	4·86
	Alternating layers of red clay and gray clay with numerous thin layers of quartz silt.			
(G) A180-1	39°07′	54°32′	2840	1·00
	Well sorted graded silt extends from the surface to 130 cm below which is a grayish brown silty foraminiferal lutite except for a 5 cm layer of muddy sand at 320 cm below the top.			
(H) A180-2	39°06′	54°11′	2840	3·60
	Well sorted graded silt extends from the surface to 70 cm below which is a foraminiferal lutite interbedded with 2 graded layers 5 and 9 cm thick. Both grade from well bedded silty lutite at the top into very coarse subangular sand at the bottom.			
(I) A180-3	39°08′	53°54′	2840	Neg.
	Few grains of sand recovered, coring tube bent.			
(J) A180-4	39°19′	52°31′		Neg.
	Few grains of sand recovered, coring tube bent.			
(K) A180-5	39°30′	51°48′		Neg.
	Few grains of sand recovered, coring tube bent.			
(L) A180-7	39°36′	50°51′		1·23
	From the top to 30 cm brown foraminiferal lutite of abyssal facies. Below 30 grey lutite gradually grades downward into well sorted silt between 95 and 100 cm. Below 100 cm dark gray foraminiferal lutite of abyssal facies.			

Letters A-L are indicated on Figure 3.

EWING, 1954). At 7 stations cores were obtained but at only 3 stations did the cores exceed 1 metre in length. At 5 stations only a few grains of sand were taken from a bent coring tube. At stations (*D*) and (*E*) (Table 1) only the upper layer of red clay

(10 to 20 cm thick) remained in the pipe after the lower portions of the core ran out between the leaves of the core retainer. The entire sample ran out of the pipe at stations (*A*), (*B*), (*I*), (*J*) and (*K*). Therefore the only cores of significant length we have from the abyssal plain are (*F*), (*G*), (*H*) and (*L*). All these cores contain sand and silt layers so it is concluded that the reason for poor recovery on the other cores is that the material was sand or silt and ran out through the core retainer. In each case a few grains of sand were imbedded in the grease around the core retainer.

Cores (*G*), (*H*), (*I*), (*J*), (*K*) and (*L*) (Heezen, Ericson and Ewing, 1954) were taken for the specific purpose of testing the prediction of Heezen and Ewing that there would be in this area an uppermost layer of graded sand and silt. The prediction was based on interpretation of the cable breaks following the Grand Banks earthquake as the work of a turbidity current triggered by slumps which in turn resulted from the earthquake shock. An upper layer of graded silt in (*G*) and (*H*) and indications of a similar layer in (*I*), (*J*) and (*K*) confirmed the prediction (Heezen, Ericson and Ewing, 1954).

In each core from the abyssal plain there is evidence of turbidity current deposition: shallow water foraminifera, graded quartz sands, grey clays and beds of silt all interbedded with lutite of abyssal facies. In five places there is an uppermost layer of sand or silt, which is graded in at least two cases.

A much greater number of cores have been taken from the rises adjacent to the abyssal plain. These sediments consist essentially of the shells of planktonic foraminifera mixed in varying proportions with " red clay " or brown lutite. Because of solution of calcium carbonate the shells of foraminifera decrease in numbers with increase in depth of water. Below about 5,000 metres shells of foraminifera are almost absent and the sediment consists essentially of brown lutite. Such sediment accumulates through a constant rain of particles from above. The particles themselves are either wind-blown or are transported by oceanic currents. Much of the calcium carbonate is precipitated organically in the upper layers of water. In any case, the route of transportation of the particles is not along the ocean floor.

Core A 160-1 (30°08′N, 57°53′W, 5,100 metres depth on the Bermuda Rise) contains typical normal abyssal sediments, free from turbidity current deposits. Throughout its length of 458 cm it is dark brown lutite. Shells of foraminifera make up less than one percent by weight of the sediment. Micronodules of maganese oxide are common. Sand and silt layers are quite absent, and there are no abrupt changes in lithology.

This contrast in sediment type between the abyssal plains and the neighbouring rises has been found in many other cases by the present writers – in the Atlantic Ocean, the Caribbean Sea, the Gulf of Mexico, etc. In several cases more than 6 metres of gray sand and silt have been found under a few centimeters of lutite in cores taken on the abyssal plains.

A further example is offered by the abyssal plains of the Western Equatorial Atlantic. Koczy (1954) apparently considered this plain between the equator and Lat. 15°N as typical of those found during the Swedish Deep Sea Expedition (1947-48). Locher (1951, 1953) reports graded beds of terrigenous sand and silt in all cores taken from this plain. The shallow water origin of this material is strongly supported by Phleger (1954), who found shallow water benthonic foraminifera in the sands of the four of these cores which he studied.

Without exception, every abyssal plain for which data are available has yielded cores exhibiting the alternations in sedimentary type characteristic of turbidity current deposits.

ORIGIN OF THE ABYSSAL PLAIN

Since the discovery and beginning of systematic investigation of abyssal plains in 1947 several explanations of their origin have been offered. Each of these is discussed in the following paragraphs, with special reference to the facts upon which it was based.

1. *Atectonic areas.* The suggestion that the abyssal plains represent atectonic areas in which the original crust of the earth has been unaffected by diastrophism since the origin of the ocean basins was made by Tolstoy and Ewing (1949). This hypothesis was offered in a highly tentative fashion on the basis of two facts : (1) the plain was flat and nearly level ; (2) the seismic reflections from the plain were of type *R* (Hersey and Ewing, 1949) which was then interpreted as evidence of thin sediments on the assumption that the sediments of abyssal plains should be like the very homogeneous sediments of the rises.

This theory was based solely on the lack of an alternative leveling process. It is no longer needed now that a better smoothing out process has been found. The seismic " *R* " reflections have been very satisfactorily reinterpreted (Ericson, Ewing and Heezen, 1952) as reflections from thinly bedded deposits in which alternate beds differ widely in lithology. The fact remains that diastrophism has not been nearly as active in the regions of the abyssal plains as in other regions, for $\frac{1}{2}$ to 1 km of sediment (Ewing, Sutton and Officer, 1954) has buried all topographic features in the area.

2. *Subaerial erosion surfaces.* The subaerial erosion hypothesis for the abyssal plains was invoked to explain apparent widespread benches and terraces found on the continental rise, continental slope, the Mid-Atlantic Ridge and on seamounts (Tolstoy, 1951). The abyssal plains were taken as the lowest of a great series of eustatic terraces. The evidence now available against subaerial erosion at great depths below present sea level is very conclusive (Ericson, Ewing and Heezen, 1951).

3. *Lava plains.* The suggestion was made by Pettersson (1953) that the abyssal plains were formed by vast outporings of lava. This interpretation was based on two facts : (1) the existence of the nearly level plains, and (2) the fact that coring tubes came up bent and empty after an encounter with the abyssal plains. The damage to the coring tubes was interpreted as the result of an encounter with solid rock. The only plausible way to explain solid rock on the flat floor of the ocean basin was to appeal to lava flows. Pettersson believed that the high thermal gradients found in deep sea sediments might support the idea that widespread lava flows in the deep sea basins were not uncommon. According to our experience the coring tubes are often bent and empty after encounters with beds of sand or gravel. Three serious difficulties with the lava plain hypothesis are : (1) the high fluidity of lava required to produce slopes as gentle as the typical 1 : 3,000 ; (2) the high speed of flow required for lava to retain this fluidity while traversing distances of 500 to 1,000 miles, particularly if required to start in abyssal depths instead of high on a continental slope ; (3) in every plain whose slope has been determined this slope is downward from an area adjacent to an obvious source of abundant sediments.

4. *Areas of long-continued sedimentation.* KOCZY (1954) suggested that the abyssal plains are merely " areas " in which the sedimentation process has been in action for a long geological period. He apparently means to imply that small scale gravity movements, compaction, folding, slumping, etc. would eventually produce a flat surface if given enough time, for sedimentation of the particle by particle type alone should cause no significant alteration of the topography, leaving the upper surface of the sediments parallel to the rock surface below. The theory of long-continued sedimentation would not explain the gradients or the type of sediments found on the plain, and it is difficult to understand how small-scale gravity movements alone could produce such a flat plain.

5. *Uniquely fine sediments distributed by bottom currents.* BROWNE and COOPER (1950) reported a " rough " gravitational field over an abyssal plain west of the Bay of Biscay and inferred the existence of large topographic features in the buried rock surface. They concluded that on the abyssal plain " the detrital mud is so finely divided that it can be carried in suspension for a very long time and gradually spread by bottom currents so as to fill in the hollows in the original topography " (p. 278).

BROWNE (1954) has apparently abandoned this hypothesis, for he states that " turbidity currents provide a natural explanation of how the ooze came to be contained in the trough of the basement rock and hence almost obliterated the surface indications of the underlying topography." (p. 399).

The sands and silts which occur on all abyssal plains studied to date contradict the hypothesis that the flatness was produced by extremely fine sediments through the action of deep ocean currents.

6. *Burial of original topography.* The hypothesis that the abyssal plains were formed by the deposits of turbidity currents which have gradually covered the original topography was made by HEEZEN, EWING and ERICSON (1951). This hypothesis was based on (1) the existence of flat, nearly level surfaces which slope away from areas adjacent to sediment sources ; (2) the occurrence of graded sand layers, shallow water benthic foraminifera, gray clays and silt layers in cores from the abyssal plains, all indications of turbidity current transportation ; (3) the partially buried appearance of seamounts which protude from the plain. HEEZEN and EWING (1952) interpreted the submarine cable breaks which occurred for 13 hours following the 1929 Grand Banks earthquake as the result of a turbidity current which ran down the continental rise and deposited a layer of graded sand on the abyssal plain to the south. In 1952 the prediction of an uppermost layer of graded sediment was confirmed by the results at five coring stations on the northern part of the abyssal plain south of Cabot Strait. LOCHER (1954) from a study of five cores taken from the abyssal plain of the western equatorial Atlantic concluded that the deep sea sands and shallow water foraminifera (PHLEGER 1954) contained in these cores were transported from the South American continent to the plain by turbidity currents. He further suggested that the flatness of the plain was the result of this process.

All the known facts concerning the abyssal plains are explained by the theory of the burial of the original topography by turbidity current deposits. This theory led us to predictions about the Grand Banks earthquake of 1929 which were subsequently confirmed, and now appear to be firmly established.

HISTORY OF THE ABYSSAL PLAIN SOUTH OF NEWFOUNDLAND

The latter part of the sedimentary and physiographic history of the abyssal plain south of Newfoundland has been controlled by topographical environment and by the supply of sediment. From cores taken on the top and flanks of the Caryn Seamount it can be inferred that this volcanic feature is older than Miocene and probably came into existence after Upper Cretaceous time. Little other evidence about the ages of the major submarine mountain systems of the area is available, and any attempt at this time to write history of the abyssal plain prior to the development of these mountains would be based entirely on highly theoretical grounds.

Turbidity currents must have brought sediments to the abyssal plain in question mainly from three directions : (1) from the Cabot Strait area ; (2) from the Mid-Ocean Canyon which carried sediments down from the Labrador and Newfoundland basins ; and (3) from the New England and Nova Scotian submarine canyons by way of the western arm of the abyssal plain. As the turbidity currents brought in more and more sediment the abyssal plain deposit increased in thickness and spread out, extending the plains farther and farther from the sediment sources. The process has now progressed to the point where the depression between the topographic highs of the Mid-Atlantic Ridge and the Bermuda Rise is filled sufficiently that a 200-mile-wide plain exists. The sediment thickness under the plain is probably quite variable. The turbidity current sediments must be thick in the north and thin toward the southern end of the plain. In this way the increase in number of seamounts protruding from the plain with increased distance from the sediment sources is related to the decrease in transporting power of the turbidity current with increasing distance and decreasing slope. The limits of the areas in which the various sources played a major part in sedimentation are clear only in the case of the Cabot Strait source versus the Mid-Ocean Canyon. The sediment contributed by the Mid-Ocean Canyon has built up a fan from the point where the canyon cuts through the southeast Newfoundland Ridge and Long. 50°W. The saddle which runs from 37°N 51°W to 40°N 50°W represents the boundary between the two areas.

The only normal-length cores obtained from the abyssal plain were taken from the southern part of the plain (*C* and *F*). The fact that the upper layer of these cores was red clay indicates that the turbidity current which followed the 1929 Grand Banks earthquake did not reach as far as these two cores. The presence of turbidity current-deposited sediment deeper in the core indicates that turbidity currents have been important in the past in building the flat floor at this locality. The fact that the finer fractions dominate in this portion of the plain is consistent with the idea that the coarser fractions have been dropped en route, as the slope gradually flattened.

Not much can be said about the rate of sedimentation in the abyssal plain except that all cores almost certainly ended in Pleistocene deposits. The difficulty stems from the fact that in these depths the clays are barren of fossils and the turbidity current deposits are of course reworked.

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Lamont Geological Observatory, (Columbia University) Palisades, New York.

Lamont Geological Observatory Contribution.

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The ratio of photosynthesis to respiration in marine plankton algae and its effect upon the measurement of productivity

JOHN H. RYTHER

Summary—Simultaneous measurements of photosynthesis in tropical ocean waters using STEEMANN NIELSEN'S C^{14} method and RILEY'S "light-and-dark bottle" oxygen technique showed wide disagreement, with C^{14} values consistently lower by a factor of 10-100. Similar comparisons made in coastal waters, gave good agreement between the two methods.

Laboratory experiments suggest that plankton algae respire to a large extent the newly-formed products of their photosynthesis. Thus, in measuring photosynthesis by C^{14} uptake, a considerable loss of activity may be incurred through respiration.

The magnitude of the error introduced by the respiratory loss of C^{14} is proportional to the ratio of respiration to photosynthesis. During exponential growth of *Chlamydomonas*, respiration is 5-10% of photosynthesis, but in nutrient starved, non-growing, cultures respiration may equal photosynthesis.

Under condition of both exponential growth and nutrient starvation, photosynthesis measurements by the C^{14} method agree with net photosynthesis (the difference between photosynthesis and respiration) as measured by the increase in oxygen in light bottles.

C^{14} values compare with total photosynthesis, determined from light-and-dark bottle experiments, only when the ratio of respiration to photosynthesis is low (e.g., during active growth). In nutrient-starved cultures, where the ratio approaches unity, C^{14} experiments give values which are lower by an order of magnitude.

THE use of C^{14} as a tracer for measuring photosynthesis rates in natural populations of phytoplankton was first described by STEEMANN NIELSEN (1952). This paper, which also included some preliminary data for mid-ocean photosynthesis from the *Galthea* expedition, was at once both stimulating and disturbing. While it provided marine biologists with a new technique, much more sensitive than existing methods, it also appeared to give values which were generally lower by a factor of 10 or more than earlier measurements of photosynthesis in similar areas of the ocean as made by RILEY *et al.* (1949) by means of the familiar "light-and-dark bottle" oxygen experiments.

Experiments were carried out at Woods Hole by RYTHER and VACCARO (1954) in which the photosynthesis of healthy algal cultures and natural plankton populations from Vineyard Sound was measured by both methods simultaneously. In general, agreement between the two techniques was extremely good. While photosynthesis values obtained by the C^{14} method were consistently lower, they were always within 50-90% of those obtained by "light-and-dark bottle" oxygen experiments*.

It was the author's tentative conclusion, based on these experiments, that the differences between RILEY'S and STEEMANN NIELSEN'S data may have reflected the seasonal or geographical variability of photosynthesis in the sea. Subsequent investigations, however, have proved this position to be untenable.

* A systematic error in the determination of C^{14} activity resulted in an overestimation of C^{14} photosynthesis by approximately 10%. Correction for this error did not appreciably effect the data or alter the authors' conclusions.

During the spring of 1954 the research vessels *Atlantis* and *Caryn* visited respectively the Antilles current north of Puerto Rico and the Sargasso Sea south-east of Bermuda. During both cruises there was a limited opportunity to conduct photosynthesis experiments using both methods simultaneously. In every case, the C^{14} method gave values which were less by a factor of 10-100 than those obtained by " light-and-dark bottle " oxygen experiments. Furthermore, in a more recent paper by STEEMANN NIELSEN (1954) an experiment was described in which the two methods were employed to measure photosynthesis of paper-filtered Sargasso Sea surface water. In this case, a discrepancy of almost 200-fold was observed. (Table I).

Table I. Simultaneous measurements of photosynthesis in tropical ocean water by C^{14} and oxygen experiments. (Expressed as mgC/litre/day).

Atlantis. 196. Antilles Current : Feb.-March, 1954. Samples from 9 m measured at 1,200 foot candles.

Lat.	*Long.*	*Oxygen method*	C^{14} *method*	O_2/C^{14}
24°28′	74°29′	·0127	·0011	11·5
23°54′	73°46′	·0348	·0007	49·7
24°12′	73°42′	·0660	·0058	11·4
20°30′	79°32′	·0264	·0029	9·1
26°37′	79°14′	·0132	·0012	11·0

Caryn. 72. Sargasso Sea : June, 1954. Samples from 10 m measured under natural surface illumination.

Lat.	*Long.*	*Oxygen method*	C^{14} *method*	O_2/C^{14}
28°53′	61°38′	·070	·0007	100·0

Galthea. Sargasso Sea : June, 1952 (STEEMANN NIELSEN). *Coarse-filtered surface water. C^{14} experiments for 12 hours at 1,800 foot candles. O_2 experiments for 3 days under natural surface illumination.*

Oxygen method	C^{14} *method*	O_2/C^{14}
·03	·00017	176·0

It became apparent from these data that, while the two methods gave good agreement in coastal waters, they did not give comparable results in the open ocean. Further laboratory experiments, which will be discussed below, suggest a possible explanation for the inconsistency of the agreement between the two methods.

In STEEMANN NIELSEN'S original description of the C^{14} method, he estimated that in a three hour experiment one-third of respiration is based upon substances produced by photosynthesis during the course of the experiment. Further studies by STEEMANN NIELSEN (personal communication) and the present author indicate that this figure may have been low, and that the algae may utilize almost exclusively the newly-formed products of photosynthesis for their respiration.

Fig. 1 illustrates that from 10% to 40% of the C^{14} fixed during two hours of photosynthesis may be lost, presumably through respiration, in the ensuing four to six hours. Since additional respiration of C^{14} undoubtedly occurred during the two hours of photosynthesis, these figures are minimal.

These and other similar experiments indicate that, while the loss of activity through respiration may be relatively large and must be taken into consideration, this loss is also extremely variable and hence cannot be accounted for by application of a constant correction factor.

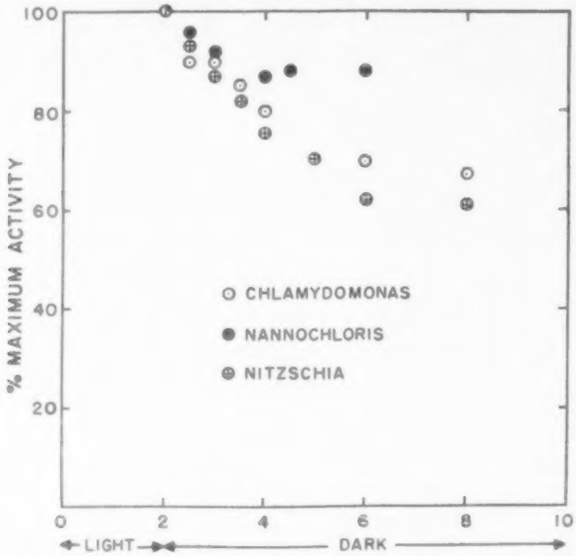

Fig. 1. Loss of activity of three species of marine algae when placed in dark after two hours exposure to light in $C^{14}O_3$.

The extent to which the respiration of C^{14} may effect the measurement of photosynthesis by the C^{14} method will depend, among other things, upon the ratio of respiration to photosynthesis. It is well known that this ratio increases with depth (and decreasing illumination) in the ocean. The term " compensation point " refers to the light intensity at which photosynthesis and respiration are equal (JENKIN, 1937) and " compensation depth " to the depth at which compensation intensity occurs. It may be assumed, however, that the respiration : photosynthesis ratio is dependant not only upon light, but equally as well upon any other factor or factors which have a differential effect upon the two processes.

KETCHUM (1939) reported a decrease in the growth rate of *Nitzschia closterium* at phosphate concentrations below ·55 mgA/m^3. RILEY *et al.* (1949) considered that photosynthesis in the ocean is limited when phosphate falls below this level, but assumes that respiration is not affected. The effects of nutrient depletion upon these two processes were investigated in the following experiment.

Photosynthesis and respiration were determined at various stages in the population development of a pure culture of marine *Chlamydomonas* by means of " light-and-dark bottle " experiments (Table II). The *Chlamydomonas* was grown in a medium deficient in nitrogen and phosphorus and cell division occurred for only 4-5 days.

Photosynthesis per cell was relatively high during exponential growth, but decreased rapidly as nutrients became limiting and continued to decline throughout the experiment. Respiration per cell also decreased during the first four days, but then remained

constant. While respiration decreased by a factor of two, photosynthesis decreased 20-fold in the course of the experiment.

Respiration was 5-10% of photosynthesis during the exponential growth phase of the culture, about 50% as the population asymptote was reached, and equal to photosynthesis after the culture had stopped dividing for 15 days. In the last instance the population was at a compensation point, but resulting here from nutrient deficiency rather than from limitation of light.

Table II. Photosynthesis (P) and respiration (R) in a nutrient-deficient pure culture of marine Chlamydomonas (Expressed in ml. O_2/24 hrs.)

Days	*Mean cell count* (10^6 *cells/litre*)	*P/litre*	*R/litre*	*P/cell* ($\times 10^3$)	*R/cell* ($\times 10^3$)	*R/P* × 100
0	26					
1-2	61	6·89	·82	113·0	13·4	11·8
2-3	135	16·40	1·35	121·0	10·0	8·3
3-4	290	5·30	2·48	18·3	8·6	47·2
4-5	390	4·10	2·30	10·5	5·9	56·3
5-6	470	4·10	2·32	10·1	5·7	56·3
6-7	427	4·08	2·70	9·5	6·3	63·0
14-15	410	3·18	2·40	7·5	5·9	78·9
28-29	415	2·47	2·52	6·0	6·1	101·8

If, as suggested, the phytoplankton respire largely the newly-formed products of photosynthesis, their up-take of C^{14} would appear to represent more nearly their net photosynthesis, or the difference between photosynthesis and respiration, rather than total or gross photosynthesis. The oxygen method, on the other hand, corrects for respiration by means of the dark bottle. By taking the difference between the oxygen produced in the light bottle (or consumed if respiration exceeds photosynthesis) and that consumed in the dark bottle, a measurement is made of total or gross photosynthesis. The preceding experiment has demonstrated that gross and net photosynthesis may be almost equal or may differ widely depending upon the state of nutrition of the organisms.

The effect which the relation between gross and net photosynthesis may have upon photosynthesis measurements is illustrated in the following experiment. Photosynthesis was measured simultaneously by C^{14} and oxygen experiments in a nutrient-deficient, pure culture of *Chlamydomonas*. Three such comparisons were made, (1) during the exponential growth phase, (2) when the population asymptote was reached, and (3) after the culture had stopped dividing for about two weeks (Fig. 2). Photosynthesis values obtained by both methods are expressed in mg. C fixed per liter per day. In the oxygen experiments (clear bar graphs) the values above the base line are equivalent to the oxygen increase in the light (the difference between photosynthesis and respiration, or net photosynthesis), the value below the base line is equivalent to the oxygen decrease in the dark bottle (respiration), and the entire graph represents gross photosynthesis. In every case photosynthesis measured by C^{14} uptake (cross-hatched bar graphs) was 70-80% of net photosynthesis. During exponential growth C^{14}-photosynthesis was 75% of gross photosynthesis. In the nutrient-deficient culture, C^{14}-photosynthesis was lower than gross photosynthesis by a factor of 20.

In the preceding experiments measurement of net photosynthesis could be made because bacteria-free cultures were used. In "light-and-dark bottle" experiments with natural populations it is not possible to separate respiration of the phytoplankton from that of bacteria and other organisms, and no estimate of net photosynthesis may be made. Consequently, the extent to which the relationships described above may occur in the ocean must remain a matter for speculation.

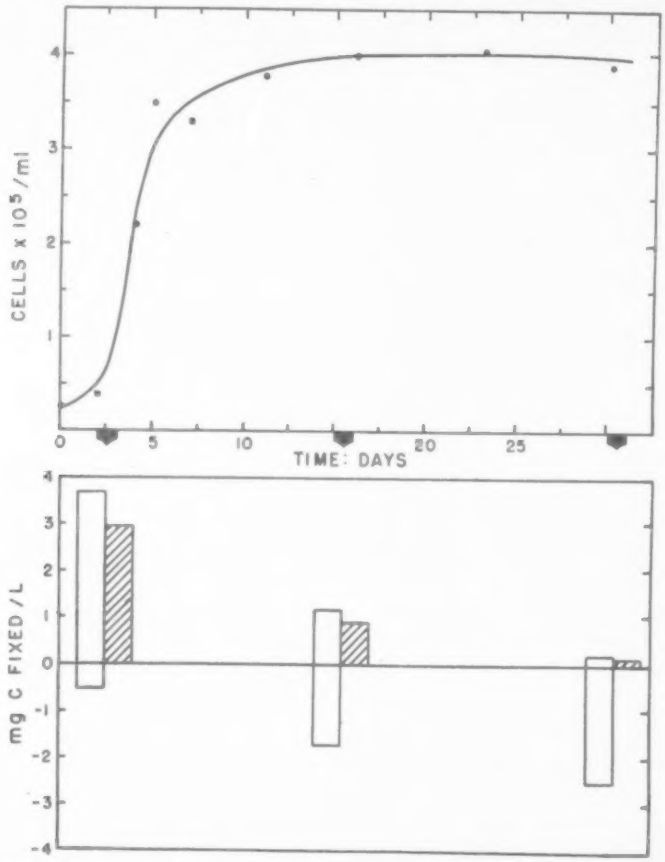

Fig. 2. Photosynthesis measured by oxygen production (clear bar graphs) and C^{14} uptake (hatched bar graphs) in a nutrient-deficient, pure culture of marine *Chlamydomonas*. Upper figure represents growth of culture determined by cell counts. (See text for full explanation of lower figure).

It may be postulated, however, that whenever nutrients (and presumably other factors) become limiting to the photosynthesis of an existing population of phytoplankton, a large difference between gross and net photosynthesis and a resulting large discrepancy between photosynthesis measurements by the C^{14} and oxygen method may be expected. In this connection, it is at least suggestive that the areas showing this disagreement occur in the tropical mid-ocean where surface concentrations of nitrogen and phosphorus are generally low and presumably are frequently limiting to photosynthesis (cf. RILEY, 1949). On the other hand, good agreement between the two methods is normally observed in relatively eutrophic coastal waters.

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Note sur les définitions des formes du terrain sous-marin, proposées par le comité International de Monaco en 1952*

JACQUES BOURCART

Summary—It is argued that fixed definitions of submarine features, as proposed by international committees, rapidly become obsolete owing to the continual progress in automatic methods of surveying. Examples of this are illustrated from the feature, Continental Shelf, with special reference to three types of shelf in the Mediterranean. Essential deep-sea features, as accepted (in English) by the International Committee on Ocean Bottom Features, are given with suggested French equivalents. Secondary and superimposed features are also briefly discussed.

LES différentes classifications qui ont été adoptées pour les formes du terrain continental sont toutes basées sur l'expérience multimillénaire des montagnards. Les mots que les géographes ont choisis sont donc empruntés aux langues vulgaires, par exemple chaîne, crête, col, cluse, falaise, etc. Les géomorphologistes (*physiographers*) ont, soit généralisé, soit spécialisé ces dénominations.

En France, des exemples cartographiques de ces différentes formes ont été donnés soit par le Général BERTHAUD, topographe de métier, soit par le Général de la Noë, collaborant avec le géologue de Margerie. Ces travaux sont essentiellement des albums et ils subsisteroant quelle que soit la variation dans les théories explicatives (*genetics*).

Il en est tout autrement des essais de nomenclature des formes sous-marines qui ont été proposées jusqu'ici par les différentes commissions internationales. Celles-ci semblent avoir, d'emblée, cherché à donner des *définitions*. Il me semble que ces définitions sont rapidement périmées par suite de l'incessant progrès des méthodes automatiques de levers. Je voudrais en donner un exemple dans le cas du groupe de formes que je connais le mieux, celles du Socle continental.

La notion de *Plateau continental*, qui semble s'être dégagée dès le XVIII° siècle, dès les travaux du Comte DE MARSILLI, est une des plus classiques de l'Océanographie morphologique. F. P. SHEPARD remarque que, pourtant, elle n'est due qu'à la généralisation de quelques rares exemples bien connus.

J'ai déjà insisté sur le fait que la notion d'un Plateau continental (*Continental shelf*) " bordant tous les continents et s'étendant de la limite des basses mers jusqu'à la profondeur où commence une augmentation marquée de la pente vers les grands fonds†" est essentiellement dû à l'usage de cartes à petites échelles, établies à l'aide *d'un très petit nombre de sondages*, surtout dans les parties profondes. L'idée classique de limiter le Plateau à un Rebord (*Edge*) ou à une rupture de pente (*abrupt change in slope at continental margin :* R. S. DIETZ et H. W. MENARD) est, à mon avis, une généralisation abusive, même dans le cas d'une zone aussi limitée que le littoral français de la Méditerranée.

Il me semble inutile d'insister sur le fait que ce Rebord est classiquement (*con-*

* v. p. 2.
† Definition du Comité international de 1952 toir *Deep-Sea Research* **I, 1,** 1953.

ventionally) placé à 100 brasses ou 200 m par suite de l'emploi de cartes générales où la première teinte bathymétrique est celle de 0 à 200 m. Il résulte de la revue que SHEPARD a donnée dans son ouvrage que ce Rebord " peut exister à des profondeurs inférieures à 65 brasses ou supérieures à 200." Mais la légitimité d'étendre cette définition du Plateau à l'ensemble des Océans n'a jamais encore été vraiment discutée.

La notion de Bordure continentale (*Continental borderland*), introduite par SHEPARD et ses collaborateurs, a seulement porté quelque atténuation à la conception d'un plateau plat auquel succéderait un " glacis†" (*Continental slope*), conduisant aux grands fonds : " Quand la zone à partir de la ligne des basses mers est très irrégulière et contient des profondeurs en notable excès avec celles qui sont typiques pour le Plateau continental, le terme de " bordure continentale " est approprié."**.

La côte française de la Méditerranée ne nous donne aucun exemple de Plateau continental qui soit limité par un *abrupt* net. Le seul cas est celui des abrupts par où se terminent vers le haut les cañons. Ces abrupts sont dus au fait que ces cañons dans le Golfe du Lion, et quelques autres, sont creusés dans un *plateau* dont la surface est faite par une dalle de calcaire quaternaire qui s'éboule dans le cañon et dont la tranche reste toujours fraîche. A Falaise Peyssonnel, décrite dans le Golfe du Lion par MARION, ne doit son existence qu'à des levés transversaux aux cañons.

Il est certain, pourtant, que de tels abrupts existent au large d'autres plateaux. Les exemples donnés par DIETZ et MENARD (Amérique du nord : San Diego, 50 br., Point Conception, 47 br., San Francisco, 72 br., Sitka (Alaska), 70 br., Aden, 43 br., Ile Pribilof 85 br.) pourraient être interprétés en les comparant aux *plateaux* du continent formés, à la partie supérieure, de calcaires ou de roches ébouleuses horizontales ou à pendage inverse de la pente, comme ceux de la Bourgogne ou de la Lorraine. Je remarquerai, en passant, que les auteurs cités donnent une coupe d'un plateau où aucun abrupt n'existe au voisinage de 50 brasses, tandis qu'un, parfaitement net, existe un peu au dessus de 100 brasses (Delaware).

Les pentes du socle continental du littoral méditerranéen de la France métropolitaine peuvent se classer en trois types :

(1) *Golfe du Lion*. Le plateau est très plat, uni, incisé à partir de 90 m. par de nombreux cañons dont la partie supérieure est verticale. Les interfluves ont une pente longtitudinale *convèxe* qui débute vers 100 m et passe par un maximum à 500-600 m. Elle devient concave vers 2.000-2.100 dans la zone de piedmont où s'accumulent les vases. Ce type morphologique correspond à une zone synclinale miocène, pliocène et quaternaire.

(2) *Massif sous-marin primaire des Maures* (de Marseille au Cap d'Antibes) : pentes convexes, depuis le Prisme continental (45-50 m.) jusqu'à 2.100 m. Mais les contre-pentes sont nombreuses, les interfluves portent des sommets et des pics ou des entassements de blocs. Les vallées sous-marines ne suivent pas la pente générale ; elles peuvent même traverser en gorges épigéniques certains bombements. Ce type est réalisé dans un horst hercynien, actuellement affaissé sous la mer.

Un exemple particulièrement remarquable de ce type morphologique est réalisé dans le " pays continental " qui réunit, à partir de l'Est du Golfe de Gênes, l'Italie

† Le mot talus, traduisant *slope* provient une fausse theorie.
** Comité International 1952.

à la Corse. Mais il s'agit d'un *continent affaissé* avec un relief subaérien typique : montagnes, pics, éboulis et non d'un " plateau continental." Le glacis (*Continental slope*) est dirigé vers les grandes profondeurs de l'Ouest (cuvette de Nice).

Ces deux exemples de pays continentaux sont comparables à la *Continental borderland* californienne, mais il s'agit d'un pays figé et non d'une zone faillée et récemment plissée comme dans le cas de la Californie.

(3) *Type Niçois*. La pente est entièrement concave du littoral à 2.300 m, disséquée en pattes d'oie par de très nombreux ravins sous-marins. Il s'agit d'une zone synclinale pliocène, argileuse, comprise entre deux reliefs sous-marins perpendiculaires à la côte, celui du Cap d'Antibes et l'abrupt rectiligne du Cap Ferrat.

Le Socle continental à l'Est de Villefranche (Monaco, Menton) est d'abord concave, puis convexe et enfin, en dessous de 2.000 m, à nouveau concave. Il semble formé d'abord de roches argileuses, puis en dessous de roches calcaires.

En résumé : 1° Le mot de Plateau ne peut être correctement appliqué qu'aux zones très continentales où la lithologie et la tectonique sous-marines ont permis l'existence d'une zone plate, limitée par un rebord vertical vers les profondeurs. En bonne langue, il s'applique aussi à des plateaux sous-marins plus profonds, comme le Plateau du Blake.

2° Dans tous les autres cas, la distinction entre " plateau " et " glacis " (*slope*) est soit difficile, soit impossible. Je pense donc que le seul mot approprié est celui de " socle " continental sous-marin. La morphologie y est toujours subaérienne, mais très variée ; elle n'est masquée que par l'envasement. Cette zone n'est pas seulement bordière (*borderland*) ; elle peut former des isthmes joignant les îles continentales comme la Corse et la Sardaigne au reste du Continent, peut-être même des ensembles entièrement sous-marins.

La recherche d'une limite entre le socle continental et les cuvettes sous-marines est celle du début des accumulations dans les cuvettes ou bassins. Les études géo physiques seules peuvent la préciser et lui donner un caractère génetique.

DISCUSSION SUR LA NOMENCLATURE DES FORMES DES OCÉANS PROFONDS

Dans un ouvrage déjà ancien : *Géographie du fond des mers*, j'ai tenté de discuter les bases de l'ancienne classification internationale. Celle qui est adoptée par le Comité International de Monaco semble se baser sur les mêmes principes : pour éviter la variabilité rapide de toute interprétation génétique, les définitions doivent être purement descriptives. Il me semble pourtant difficile de ne pas essayer, à la lumière de ce que nous connaissons de la morphologie contientale, de jeter les bases d'une classification raisonnée. Il me semble que les formes océaniques, en relief ou en creux, sont tantôt des formes essentielles, ou harmoniques (probablement tectoniques), tantôt des formes surimposées : en relief, d'origine volcanique ou parfois corallienne, en creux, dues au tassement, à la dissolution ou, peut être, à la fusion du substratum solide. Une troisième catégorie de formes est due à l'érosion, quelle que soit sa nature. Celle-ci produit toujours des formes *concaves* vers le ciel : cirques, cañons et vallées. Il est toujours possible, comme Albert de Lapparent l'a fait pour les chaînes de montagnes continentales, de combler ces creux produits par l'érosion. Les formes concaves disparaissent alors et la surface enveloppante nous restitue à peu près l'allure de la déformation tectonique. Un travail analogue

a été fait pour le glacis continental californien par Ph. KUENEN, en supprimant les crochets des courbes de niveau qui sont dus au cañons sous-marins.

En utilisant la nomenclature admise à Monaco, je classerai ainsi les formes du terrain :

FORMES ESSENTIELLES

A. FORMES DONT LE GRAND AXE EST DE MÊME ORDRE QUE LE PETIT AXE

a EN RELIEF

Rise traduction française littérale *surélévation* ; le mot " dorsale," souvent employé pour la chaîne médio-atlantique s'appliquerait beaucoup mieux à des surélévations dont le grand axe est très supérieur au petit axe. Quand ces deux sont sensiblement égaux, le terme de *dôme* ou de *bouclier* serait préférable. En tout état de cause, cette dénomination suppose de faibles pentes : exemple, Bouclier de Pâques. Le mot de *hill* colline peut s'employer pour des reliefs où toutes les dimensions sont faibles.

b EN CREUX

Basin traduction française *bassin* est le correspondant en creux surtout du mot bouclier. Il peut s'employer dans tous les cas où la différence entre les deux axes a et b n'est pas trop grande (ellipse) et où la pente des flancs n'est pas trop forte. Dans le cas opposé, le mot français *sillon* est celui qui convient le mieux pour les fosses profondes (*trench*) qui bordent les guirlandes insulaires et les cordillères ; il correspond à " l'avant-fosse " des tectoniciens.

B. FORMES DONT LE GRAND AXE EST TRÈS GRAND PAR RAPPORT AU PETIT AXE ET LES PENTES TRANSVERSALES TRÈS FORTES.

a EN RELIEF

Ridge traduction française *chaîne :* c'est la dénomination de la géographie terrestre. Elle n'est pas génétique (chaînes tectonique, d'érosion, volcanique). Une chaîne, peut être formée de chaînons séparés par des couloirs d'origine tectonique ou dus à l'érosion (vallées longitudinales).
Les termes *sill* et *gap* s'emploient pour des ondulations *tranversales* de la ligne sommitale. Il semble manquer les mots de " culmination " ou "sommet."

b EN CREUX

Trench traduction française *sillon*. Le terme *sill* = seuil correspond à une surélévation transversale dans un sillon.

FORMES SECONDAIRES (vraisemblablement dues à des fractures)

KOCZY (1954) a insisté sur le fait que, dans l'Océan Indien, il existait des abrupts qui ne peuvent être expliqués que par des fractures. Les escarpements du type du Mendocino Scarp, rentrent dans cette catégorie. Des formes en relief, comparables aux *horsts* terrestres, ou en creux, comparables aux *fossés* (*rift valley, graben*) sont produites par ces fractures.

FORMES SURIMPOSEES

Les formes surimposées en relief sont volcaniques : *seapeak* = cône sous-marin, *seamount* (*guyot* ou *cône tronqué*). Le mot *seaknoll* demande â être réservé aux récifs submergés. En creux, le terme *deep* (fosse), ne peut s'employer que pour une forme sans liaison avec l'architecture générale de l'Océan. Le type est à chercher dans les mers intérieures par rapport aux guirlandes insulaires. Le mot *depth* n'a aucune signification morphologique.

Le terme *deep-sea terrace* semble s'appliquer à des plateaux continentaux ennoyés, comme le Plateau du Blake.

Les mots *Submarine canyon* et *submarine valley*, ne nécessitent pas de définition. Pour leur inverse, le mot *crest* = crête, me semble préférable au mot *scarp* pour indiquer une paroi verticale *due à l'érosion.*

Le mot *bank* (*banc*) semble se s'appliquer qu'à des formes glaciaires d'érosion ou surtout d'accumulation ou à des formes corraliennes submergées.

Il reste à définir le mot *plain* (*plaine*) qui semble s'appliquer aussi bien à de grandes étendues où la vase a réalisé par accumulation une surface presque horizontale qu'à des épandages volcaniques. La surface de ceux-ci peut-être soit hérissée (comme les cheires d'Auvergne (observation de KOCZY) ou accidentée de cônes volcaniques.

Paris Sorbonne

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Underwater telemetering

A telemetering depth meter

WILLARD DOW

Summary—This report describes an inexpensive telemetering depth meter capable of determining depth of towed gear and other information, and of transmitting the data acoustically through the water to the surface. The device is somewhat unusual in that it uses the ocean rather than the air as the metering medium. Built into a torpedo-shaped fish for towing purposes, the instrument is self-contained and may be quickly attached to any trawl wire.

INTRODUCTION

A TELEMETERING depth meter which can be made to determine depth of gear, current flow, or other information and then transmit the data acoustically through the water has been developed at the Woods Hole Oceanographic Institution. The acoustic signal is detected at the surface by a hydrophone connected to a sonar or low frequency radio receiver in the ship. The depth meter unit is self-powered and may be clamped on to any trawl wire in a few moments.

The device is somewhat novel in that it uses the ocean itself as the telemetering medium. That sound travels great distances through water with little attenuation has been known for many years, and highly efficient echo ranging and echo sounding equipment has been developed which takes advantage of this phenomenon. A sound " carrier " signal can be modulated or coded at the transmitter in accordance with the information desired by employing the same principles and coding techniques already developed for sonobuoys and radiosonde. The carrier is " tuned in " at the ship much as a broadcast is tuned in on a radio, and then demodulated or decoded to recover the original information just as music or speed is detected and reproduced by a radio set. In fact, a long wave radio receiver can be used without alteration for detecting the acoustic signal by replacing the radio antenna with an underwater antenna – i.e., a receiving hydrophone.

REVIEW OF CURRENT METHODS

Equipment developed to date for oceanographic research may be roughly divided into classes. The first consists of instruments which, when lowered over the side of the ship, produce a reading or a record which can be inspected when the device is recovered. The Bathythermograph (SPILHAUS 1937), bucket thermometer, and Nansen Bottle are examples of this type of instrument and they have a number of special advantages. They are simple, rugged, and compact. Being self-contained, they require no electrical cable to the ship. They have the disadvantage of providing data which may be valid only for a very small area or during a short space of time, and of making such information available only upon recovery of the instrument. In those parts of the world where conditions in the sea are reasonably homogeneous these factors are of minor importance, but in regions where conditions may vary

significantly within a relatively small area, or are subject to rapid changes, instruments which can supply continuous information without constant attendance are much to be preferred, and may be essential in some instances.

The second class of instruments, exemplified by various depth (VON ARX 1950) and current meters (UFFORD 1946) do provide continuous monitoring, but have the disadvantage of requiring electrical cables to transmit the information to the ship. Anyone who must operate such equipment at sea soon discovers that cables are a nuisance to handle on deck, that they readily become tangled with trawl wires, nets, or other gear being towed at the same time and even on occasion become fouled in the screws. Often they are subjected to sufficient strain and wear as to eventually leak or break. Replacement can be a time consuming and expensive process.

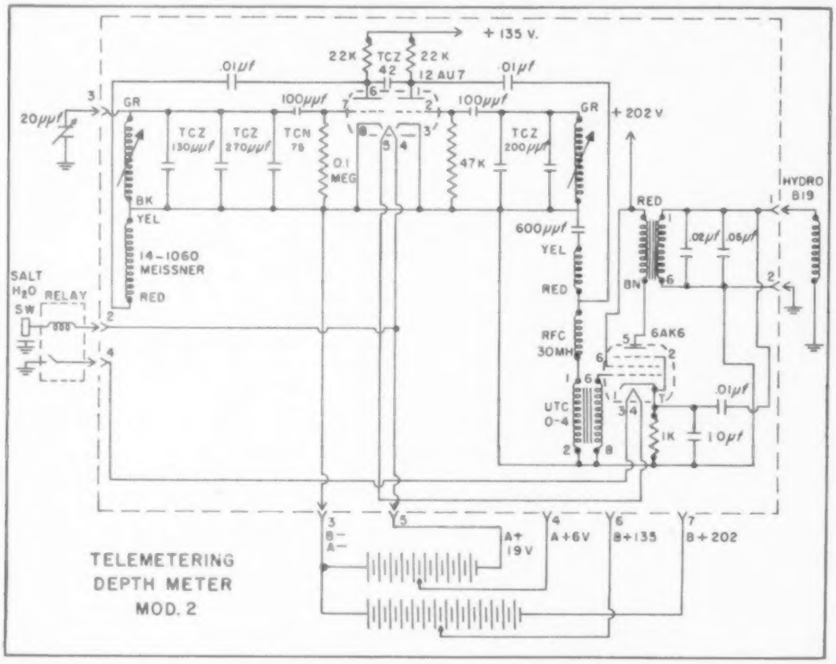

Fig. 1. Schematic diagram of telemetering depth meter.

Telemetering equipment can be designed to incorporate the best features of both classes of instruments without incurring their disadvantages. It can be made rugged, compact, self-contained and yet capable of supplying continuous information to the ship. Once submerged, the gear operates without attention for long periods of time. In fact, if data is desired from a point somewhat remote from the ship, the telemetering unit can be attached to a floating buoy by an ordinary wire or rope and suspended at any desired depth below the surface. A remote hydrophone could be effected by equipping such a buoy with a receiving hydrophone and amplifier-modulator. The information received by the hydrophone would be amplified and transmitted through the water to the ship as modulation of the carrier signal in the

manner described above. Alternatively the same instrument might be used as a deep hydrophone by suspending it from the ship's hydrographic wire, thereby eliminating the necessity for a special electrical cable capable of withstanding the severe strain.

These are only a few of the many possible applications. Telemetering units of this nature can do much to satisfy the long existent need for compact self-contained instruments capable of supplying continuous information about the ocean to a ship at sea.

GENERAL DESCRIPTION OF THE TELEMETERING SYSTEM

The telemetering depth meter makes use of the principles described above. The need for this equipment became particularly pressing when it was required to tow plankton nets and fish trawls in scattering layers. This operation requires that the depth of the plankton nets and fish trawls be known and monitored continuously.

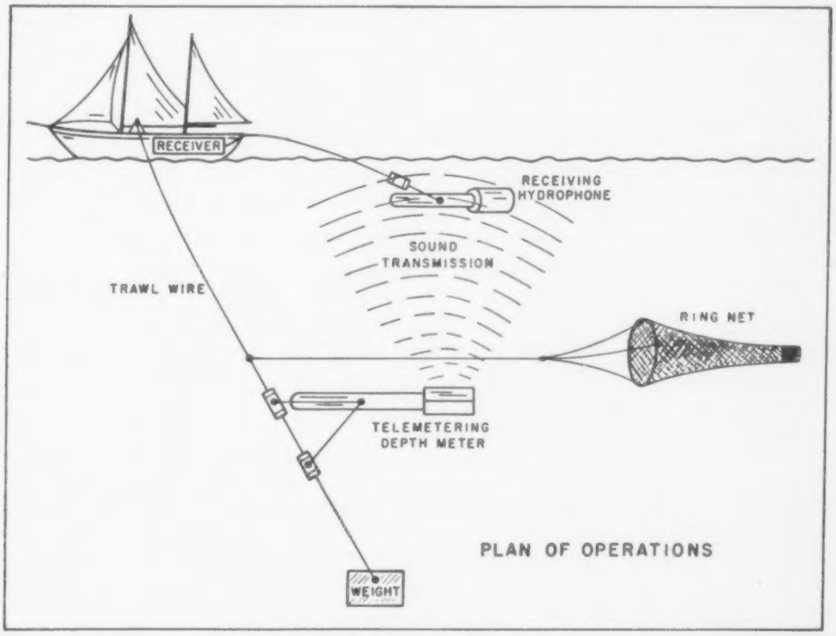

Fig. 2. Plan of operations.

The instrument determines this depth and continuously transmits the information acoustically through the water to the ship. The submerged fish contains a stable heterodyne oscillator (Fig. 1), the frequency of which is varied between 16 and 26 kc. by a variable capacitor which in turn is driven by a bourdon tube sensitive to pressure and having access to the sea. As the instrument descends, the increasing water pressure causes the bourdon tube to rotate the capacitor and the frequency of the oscillator increases. The oscillator output is amplified by a power vacuum tube and applied to a transducer in the tail of the fish. The sound radiated by the transducer is picked up by a receiving hydrophone, which is towed behind the ship at the

surface (Fig. 2). The hydrophone is connected to a tuned receiver in the vessel. As the tuning dial of this receiver is calibrated in terms of frequency, reference to a frequency vs. depth curve gives the depth of the instrument, or alternatively, the dial may be calibrated directly in terms of depth. Current or temperature information can be applied as a modulating signal on the depth " carrier signal " in accordance with the principles outlined above.

STRUCTURE

The instrument is self-contained in a torpedo shaped housing, or fish, about 53 inches long and 3½ inches diameter (Fig. 3). The housing is divided into three compartments separated by watertight bulkheads (Fig. 4). The forward compartment contains the bourdon tube and the variable capacitor fastened to it as well as the relay which acts as a power switch. The middle compartment contains the electronic chassis and battery stack. The aft compartment houses the forward end of the transducer and its cable and is removable from the rest of the housing as a unit. Connections between compartments are made by sealed feed-through connectors. The watertight bulkheads prevent damage to the electronics if either the bourdon tube or transducer should become damaged or leak.

MOUNTING

The depth meter fish is mounted on the trawl wire by a triangular bracket (Fig. 3). The fish is free to rotate in a vertical plane in the bracket so that it can always swim parallel to the surface. The bracket is free to swivel about the wire but cannot move vertically because of the stops. The swivels and stops are of a new quick-disconnect design which permits the instrument to be mounted or removed in a few seconds time (Fig. 5). The trawl wire slips into a slot on the side of the clamp. An L-shaped piece of brass is then inserted from the top into a slot at right angles to the first slot. The handle on the opposite side is then turned clockwise. This operates a screw which in turn forces a vertical grooved bar against the wire. The wire is thereby effectively clamped between this bar and the L-shaped insert. To disconnect, the procedure is simply reversed. The swivels are of similar construction except that the clamping feature is omitted. A weight or depressor is hung on the lower end of the wire to obtain a reasonable angle of tow.

OPERATING PROCEDURE

Hydrophone Placement. Experiments at sea indicate that the main obstacle to good reception of the depth meter signal is screw noise from the towing ship. For example, the non-directional hydrophone (Fig. 6), must be towed 1,000-1,500 feet behind the vessel before this background ceases to limit the sensitivity of the system. However the performance of the directional unit (Fig. 7) appears far superior in this regard, as might be expected, and tests are under way to determine if revised towing arrangements and orientation will permit it to be used close to the ship.

Depth Meter Placement. When the hydrophone is in the water the depth meter is lowered just below the surface. This automatically starts the electronic oscillators by completing a relay circuit through a salt water switch which is mounted on the nose of the fish. (The switch also insures that the device cannot accidentally be left operating when not in use and thus prolongs battery life.) The instrument

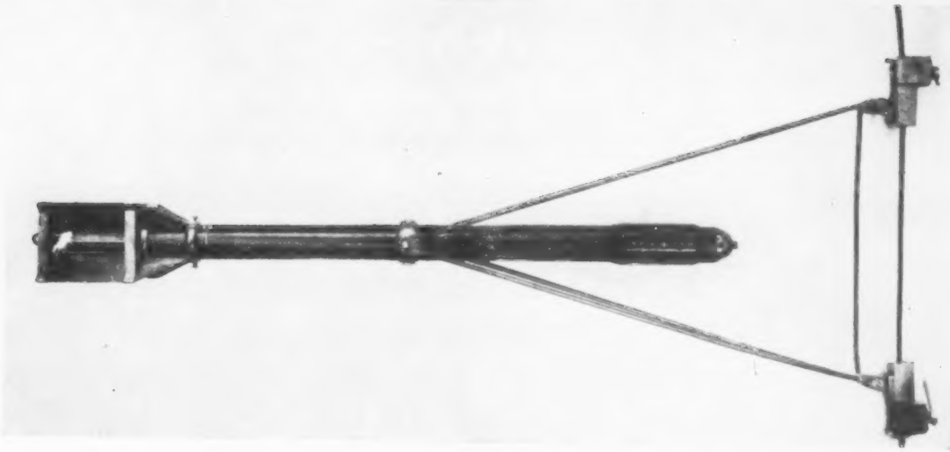

Fig. 3. Depth meter mounted on trawl wire in towing position.

Fig. 4. Telemetering depth meter interior chassis and transducer.

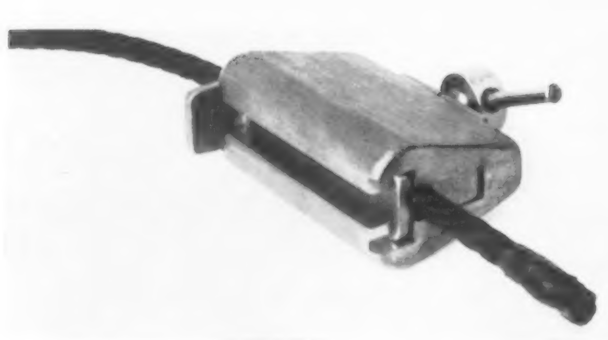

Fig. 5. Wire clamp.

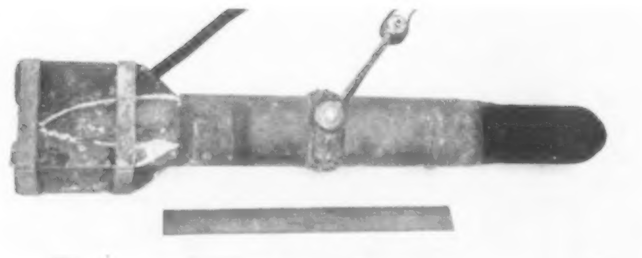

Fig. 6. Non-directional towed hydrophone.

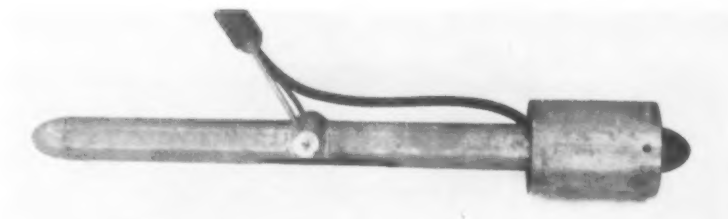

Fig. 7. Directional receiving hydrophone.

should remain in this position a few moments until a stable zero depth reading on the receiver indicates that the electronics have reached operating temperature, the unit may then be lowered to the desired depth.

Operating Time. Battery life, using mercury batteries, is approximately four hours. Since the average net tow does not usually exceed this time period, and since battery pack replacement is quick and easy, it was deemed inadvisable to increase the bulk and weight of the instrument to provide longer battery life.

Receiver Tuning. To receive the depth meter signal, the beat frequency oscillator is turned on and the main receiver tuning dial adjusted until an audible note indicates the carrier has been picked up. This note is then adjusted for zero beat and the frequency read from the receiver dial. A glance at the frequency versus depth calibration curve will then give the depth, or alternatively the dial may be calibrated directly in terms of depth. If the signal becomes weak some readjustment of hydrophone position may be to advantage.

SEA TRIALS

"*Blue Dolphin*" *Cruise.* A preliminary model of the device was given a sea trial during a 10-day fishing cruise aboard the schooner *Blue Dolphin* in August 1953, where it was used to determine the depth of fishing nets during trawling operations. It was found that the signal could be heard reliably at depths up to 1,500 feet by means of a non-directional hydrophone towed behind the ship (see below), but was intermittently lost in screw noise at greater depths. However, the meter could readily be heard to 3,200 feet when the ship was not under way. Calibration of the instrument was checked during the towing operations by echo sounding on the unit from a following vessel. Comparisons of the echo sounder and depth meter records for these runs yielded differences ranging from 4·8% to 8·3% of the depth (as determined by the echo sounder). However, it was found that the depth meter oscillators had been somewhat over compensated for temperature changes. A rough determination of the error from this source was made before the final run and applied as a correction to the telemetered signal. Comparison of records for this run indicated a deviation of only 6 feet in a 343-foot determination. This would correspond to an error of 1·8% for the depth meter reading, but since the echo sounder readings may also have been in error by this amount, this value is only an approximation. In the course of these runs a complete depth versus wire out curve was established for the net and depressor unit, and the curve was used in tests on a second expedition as described below.

"*Atlantis*" *Cruise.* Following the *Blue Dolphin* cruise, the depth meter was stabilized for temperature changes in the laboratory and then given additional tests on *Atlantis* cruise 196 to Puerto Rico. During this cruise the readings of the instrument were checked in two ways.

First a net-depressor-depth meter assembly practically identical to the one used on the *Blue Dolphin* cruise was towed at various depths and depth meter readings were taken to depths of 1,080 feet. The length of wire out and the wire angle were recorded, and the depth meter readings then compared with values taken from the depth vs. wire out curve described above (Fig. 8). While there was undoubtedly some error in applying this curve to the *Atlantis* operation, nevertheless the mean

difference between values taken from the curve and the depth meter readings was only 13·0 feet which represents 0·9% of full scale for the depth meter (1,530 feet).

The second check consisted of a vertical lowering with the ship hove to. During this test the depth meter frequencies were plotted against length of wire out as read by the *Atlantis* meter wheel for 18 different depths. The resulting curve was then compared with the original laboratory calibration curve (Fig. 9).

There are thought to be two principal sources of error in these experiments. First, the laboratory calibration follows a smooth curve, but the meter wheel calibration curve is erratic particularly at shallow depths (Fig. 9). This may be due to slippage

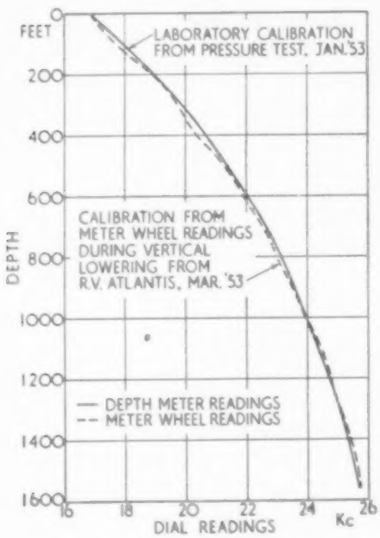

Fig. 8. Depth vs. frequency curve for depth meter. (Depth readings from depth vs. wire out curve described in text).

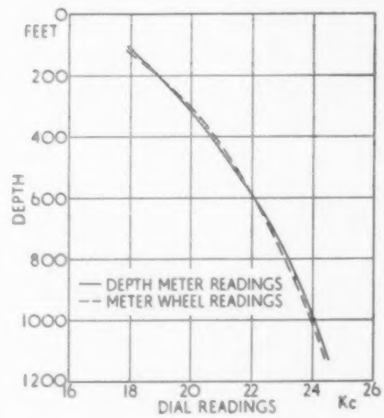

Fig. 9. Depth vs. frequency calibration curves for telemetering depth meter.

between the wheel and trawl wire when the tension is light. Secondly, the receiver dial was calibrated only to 0·1 kc. which with this depth range corresponds to 16 feet. Since the mean difference between the meter wheel and laboratory curves is approximately 13 feet, a considerable portion of this discrepancy could be due to reading error. A more finely divided receiver dial is desirable for future work.

It should be pointed out that if greater accuracy is desired at shallow depths, an alternative " nose " for the fish containing a low pressure bourdon tube can be plugged in. One of these units containing a 500-foot bourdon was taken on the *Atlantis* cruise, but was not used because the scattering layer investigations were concentrated around greater depths.

NEW DEVELOPMENTS

A new and more efficient model of the instrument having higher output power and lower battery drain has recently been developed at the Woods Hole Oceano-

graphic Institution. The new instrument has provision for applying temperature information as modulation of the carrier signal. The carrier frequency simultaneously provides depth information as in the older unit. If the instrument proves successful it will be made the subject of a future report.

ACKNOWLEDGMENTS

The author wishes to thank the following people for substantial contribution to this project:

Dr. J. B. Hersey made suggestions concerning types and placement of transducers involved in the acoustic link as well as recommendations concerning the towed fish. Mr. S. T. Knott designed and helped fabricate the structure of the depth meter, mounting bracket, towed hydrophones, etc. and helped test the equipment both in the laboratory and at sea. He also contributed substantially to other phases of the work. Mr. W. E. Witzell assisted Mr. Knott in the work outlined above. Dr. Benjamin B. Leavitt assisted in the overall design of the towing assembly and he and Dr. R. H. Backus helped test the equipment at sea. Mr. M. E. Edwards constructed the electronic chassis for Mod. 1 and 2 of the equipment. Mr. H. A. Cain constructed the special battery packs designed for the instrument.

Contribution No. 729 *of the Woods Hole Oceanographic Institution. This work was supported under Contract NObsr*-43270 *with the Bureau of Ships.*

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Deep-Sea Research, 1954, Vol. 2, pp. 152 to 158. Pergamon Press Ltd., London.

Coiling direction of *Globorotalia truncatulinoides* in deep-sea cores

DAVID B. ERICSON, GOESTA WOLLIN and JANET WOLLIN

Summary—It has been found that the Recent population of *Globorotalia truncatulinoides* (d'Orbigny), a planktonic species of the Foraminifera, in the North Atlantic may be subdivided into provinces which are distinguished by dominance of either right or left coiling shells. Counts of right and left coiling shells in samples from long sediment cores show that the ratio between right and left has changed more or less frequently during the late Pleistocene. These changes in the coiling ratio define zones which are useful in making fairly precise correlations between sediment cores.

INTRODUCTION

DURING the past several years a large collection of deep-sea cores from the North Atlantic and neighbouring seas has been brought together at the Lamont Geological Observatory of Columbia University. Early in the investigation of these cores it was realised that in order to test certain theories of deposition a method of making fairly precise correlations from core to core was needed. At about this time BOLLI (1950, 1951) published two papers in which he showed that in the evolution of certain species of planktonic foraminifera there has been a trend towards dominance of a single direction of coiling and he suggested that coiling ratios might have application to stratigraphy. The writers had already noticed that the ratio of dextral to sinistral shells of *Globorotalia truncatulinoides* varied from place to place. Stimulated by BOLLI's findings we have made counts of the shells of this species in a fairly large number of samples. From these counts it is apparent that several large provinces in the North Atlantic are defined by dominance of one or the other direction of coiling.

In accordance with BOLLI we follow the gastropod convention in defining the direction of coiling. That is, a shell is right coiling or dextral, if, when viewed from above with the dorsal side up, the chambers have been added in clockwise direction. Examples of right and left coiling shells are shown in Plate 1. In most cases the ratios have been determined from counts of over one hundred tests.

The long cores in the Lamont collection were taken with a modified KULLENBERG (1947) piston coring tube. This has two important superiorities over the pistonless coring tube. With it much longer cores can be taken. Also there is no appreciable vertical shortening of the sediment section by squeezing aside of soft layers as friction between the sediment and inner wall of the tube builds up. Burrows of circular cross-section at depths of six or seven metres below the surface are good evidence, we believe, that no shortening by squeezing has taken place. Occasionally unfilled burrows are found but even these retain an undistorted cross section. We are, therefore, quite confident that when correlatable zones differ in thickness from core to core it is because of a real difference in rate of sediment accumulation and not because of changes in the section due to the coring process.

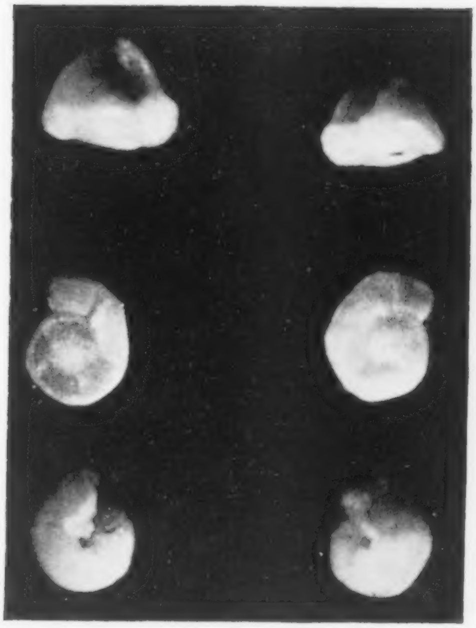

Plate 1.

COILING DIRECTIONS IN THE NORTH ATLANTIC

Three great provinces of the North Atlantic are defined by now living populations of *Globorotalia truncatulinoides*. These populations are distinguished by a dominance of one or the other coiling direction. As the chart (Fig. 2) shows, the northeast quadrant of the North Atlantic contains a population in which right coiling is dominant. A central zone of left coiling extends from northwest Africa to North America. The third province includes the equatorial Atlantic, and extends through the Caribbean, the Gulf of Mexico and back into the Atlantic by way of the Florida Straits beyond which it is poorly defined because of scarcity of the species.

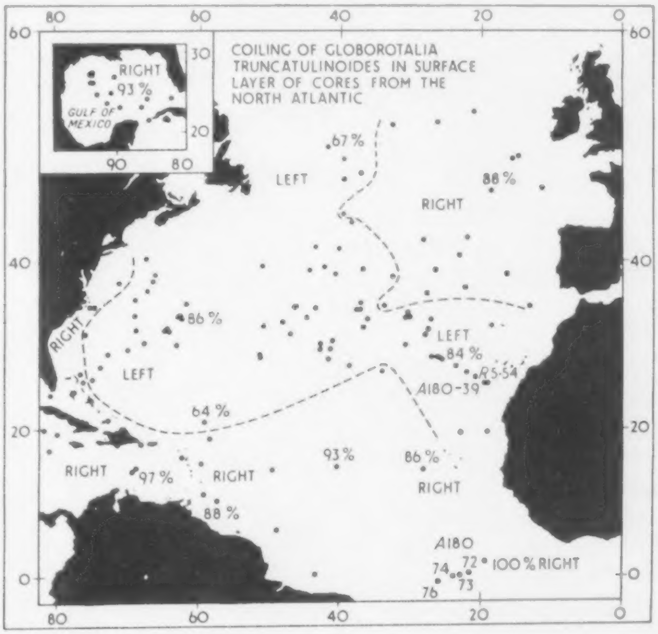

Fig. 2.

The chart is based on counts of right and left coiling shells in samples from the tops of cores. About half the cores sampled were pilot or trigger weight cores. As these short cores are taken in plastic liners which can be kept upright until sampled in the laboratory, the uppermost millimetre of sediment remains undisturbed and uncontaminated, and the contained Foraminifera should be really representative of the assemblage living in the waters above. The long cores, on the other hand, must be taken on board the ship in a horizontal position. Inevitably the soft top sediment by flowing becomes somewhat mixed and a part may even be lost. However, comparison of long core tops with corresponding trigger weight core tops shows that usually the difference in coiling ratio amounts to only a few per cent. In no case has there been found a difference in sense of coiling.

Where the depth of water exceeds about 5,000 metres the bottom sediment contains few or no Foraminifera. Such an area, the Nares Basin, lies to the southeast of Bermuda. Although we have cores from the basin it must, for the time being, remain a blank space on the coiling chart.

Over one hundred coiling ratios from top samples have been plotted but because of the small scale of the chart only a few representative ratios are shown. As a rule the ratio of preferred coiling increases with distance from the boundaries of the provinces. At and near the boundaries, dextral and sinistral shells occur in about equal numbers.

VARIATION IN COILING DIRECTION WITH TIME

In Fig. 3 the coiling ratio curves of two cores taken at stations about 360 km. south-west of Tenerife, Canary Islands, are compared. The stations are 28 km. apart and within the left dominant province. However, the coiling ratio curves of these cores show that left coiling dominance has been an exceptional condition in this part of the Atlantc. During deposition of 80 per cent of the section right coiling has been dominant. Fortunately for the student of deep-sea sediments there have been two swings of short duration to the left, which give well defined points on the curve by which to correlate.

In both cores there has been some displacement of sediment by burrowing animals. Although this must have brought about vertical mixing of sediment, it is clear from such well defined points as those at 127 cm in A180-39 and at 73 cm in R5-54 that mixing by burrowers has not seriously displaced the Foraminifera.

An interesting by-product of this particular coiling correlation is the proof that sediment accumulation at station A180-39 has been markedly more rapid than at R5-54. Both cores are composed of uniform foraminiferal lutite without sand or silt layers. Absence of winnowed layers at the shallower station, R5-54, rules out bottom scour as an explanation for slower deposition there. Evidently the difference in rates of accumulation is not due to relative distance from the source of terrigenous sediment because the station of more rapid accumulation is the more remote from the African coast. There is no evidence of greater productivity of lime-secreting organisms at A180-39. Not only is the calcium carbonate content of the two cores nearly the same but shells of Foraminifera actually make up a larger fraction of the sediment in R5-54 where deposition has been slower. For the sake of completeness the possibility that the coring tube penetrated the sediment at an angle from the

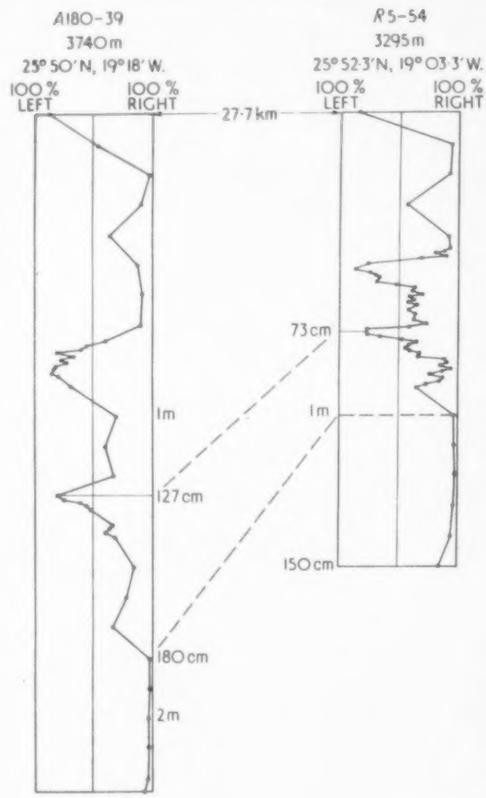

Fig. 3.

vertical when core A180-39 was taken should be considered. However, if the greater thickness of the section in A180-39 were entirely due to this cause, it would be necessary to suppose that the core was taken at an angle of 55° from the vertical. It is hardly conceivable that this could have been the case without at least some bending of the coring tube. Positive evidence that the coring tube was essentially vertical when the core was taken is afforded by well defined layering in the lower part of the core. These layers are at right angles to the axis of the core.

That the more rapid accumulation has taken place at the deeper station suggests that turbid water flowing along the bottom has been channelled by bottom topography. However, core A180-39 contains none of the usually accepted evidence of turbidity current deposition. Experiments at the observatory have shown that very much attenuated suspensions of extremely fine sediment will flow down gentle slopes under clear water at velocities in the order of a few centimetres per minute. As KUENEN and MIGLIORINI (1950) have pointed out, the thickness of the layer of turbid water in nature will lead to higher velocities. However, counteracting the thickness effect will be the smaller angles of slope of the ocean bottom, if we appeal to this process to explain the broad abyssal plains of the North Atlantic. If this kind of turbidity flow does take place in nature, it would surely not leave evidence in

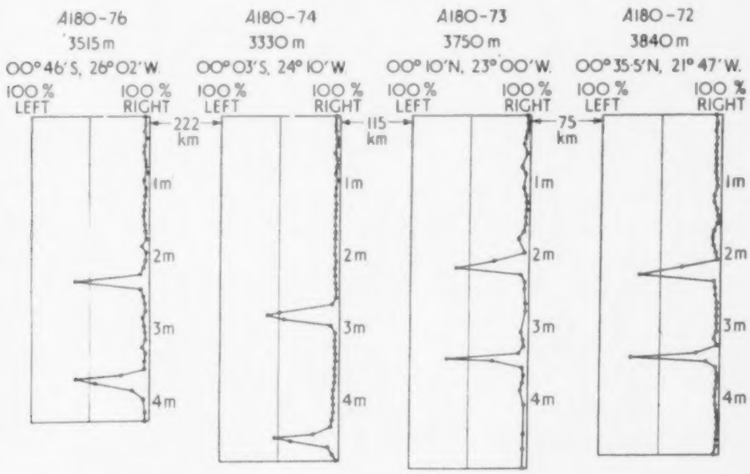

Fig. 4.

the form of graded bedding. The consistent proportionality between the coiling curves of the two cores proves that net accumulation at A180-39 must have been at a nearly uniform rate from year to year. A fairly continuous, or perhaps seasonal, supply of turbid water from the African coast does not seem too improbable. Any fine layering due to seasonal differences would be obliterated by burrowers.

ERICSON, EWING and HEEZEN (1952) have called attention to the levelling effect on bottom topography to be expected from rapid deposition by swiftly moving turbidity currents. In these two cores we again have evidence of a process of deposition favouring deeper stations. Although the tempo here is of a different order, the levelling effect by filling of depressions will be the same in the long run.

Fig. 4 shows the coiling curves of four cores from a profile 475 kms long crossing the Mid-Atlantic Ridge at the Equator. Though these differ in detail from the curves of the northern cores, there is a suggestion of correlation in that there are two well defined swings to the left. However, no firm correlation can be made until more cores from intermediate stations have been analysed.

Whether layers defined by coiling are strictly synchronous deserves a word or two. The distance separating A180-39 and R5-54 is so short in proportion to the extent of the coiling provinces that it is reasonable to suppose that the layers defined by left coiling are as nearly synchronous as paleontological zones ever are. The cores of the equatorial suite are farther apart. If, however, left coiling was a condition which spread from core to core with a long time lag, one would expect thickening of the zones in one direction or the other. As there is no consistent thickening it is probable that the layers are essentially synchronous.

On the other hand, the left zones of the equatorial suite and those of the northern cores are probably not closely synchronous, even if interdependent. From the curves of A180-39 and R5-54 it is evident that in the region southwest of the Canaries left coiling dominance is a condition which has come about within the last several thousand years judging from the thickness of the Recent left coiling layer. However, left coiling dominance has not yet spread to the equatorial region. If the lower left zones of the equatorial cores were due to gradual spread of left coiling dominance from north to south at the rate suggested by the Recent layer, we must admit the probability that the left layers of the Equator were deposited some thousands of years later than those in the north.

Cores A180-72 and 73 from very nearly the same depth of water show closely similar rates of accumulation. Cores A180-74 and 76 from the west flank of the Mid-Atlantic Ridge and from shallower water show more rapid deposition, particularly A180-74, the shallowest of the suite, which was deposited some 30 per cent faster than A180-73. The relationship here between rate of accumulation and depth of water is the reverse of that found in the northern cores. It is, however, consistent with the regional topography. All four cores were taken on the flanks of the Mid-Atlantic Ridge. The stations being separated from the continents by areas of much deeper water could not be reached by turbid water flowing down slope from the continents. Whatever terrigenous sediment they have received must have arrived as wind blown dust and in suspension wafted along by ocean currents. These modes of distribution would deal about equally with the four stations. More rapid accumulation at the shallower stations is probably partly, and perhaps mostly, due to less solution of the fine calcareous fraction. A contributing factor may have been greater productivity of lime secreting organisms in the vicinity of A180-74.

CONCLUSIONS

Since we know little about the living habits of planktonic Foraminifera in general it appears futile at this stime to attempt to conceive a theory to explain coiling direction preference in *Globorotalia truncatulinoides*. There are, however, a few deductions from evidence in the cores which at least narrow the range of possible causes.

From the thickness, about 10 cm, of the Recent layer of left coiling dominance in cores from the central zone it is apparent that the left coiling province has been

in existence for at least as long as 2,000 years and probably a good deal longer. At the same time we know from the equatorial cores that the southern right coiling province has existed continuously for at least some tens of thousands of years. Now, not only is there no physical barrier between the provinces but distribution of the species is in fact continouous from one province to the next. In 2,000 years in the absence of any other influence mixing of populations by oceanic circulation and diffusion ought to have taken place. Since this has not happened we conclude that coiling direction dominance must somehow be maintained by selection or some environmental factor favouring one direction in preference to the other.

This conclusion is not inconsistent with BOLLI's finding that there is a secular trend in the life of a species which leads from randomness to strong dominance of one coiling direction throughout its geographical range. *Globorotalia truncatulinoides* is a relatively young species. Some indecision as to its coiling direction is expectable. In sharp contrast is the old species, *Globorotalia menardii* (d'Orbigny), which has attained a very high ratio of left coiling. In all our samples from the Atlantic and neighbouring seas the ratio is above 90 per cent left. Probably the Recent form is left coiling throughout its geographical range. At any rate, all published figures of Recent specimens from other oceans, which the writers have seen, show it to be left coiling. We do not think that this is an example of orthogenesis. More likely, as with *G. truncatulinoides*, there is, and has been, something about the environment which strongly favours survival of those individuals of the species having a particular coiling direction.

Perhaps the geometry of the shell is not the decisive character. Although *G. menardii* and *G. truncatulinoides* occupy the same parts of the North Atlantic, the one species has evolved to the left while the other shows a tendency to evolve towards right dominance. This suggests that the coiling is incidental, but may be genetically linked with some other character of survival value.

From the coiling curves of *G. truncatulinoides* it is evident that left coiling dominance has been exceptional during the late Pleistocene. It is also clear that the central province of left coiling has come into existence in Recent time, that is during the last ten thousand years. In what way have conditions in this wide region of the North Atlantic become exceptional ? Perhaps the answer to this question is somehow bound up with the instability of the Recent climate.

In the meantime, these coiling ratios may be put to use in measuring relative rates of accumulation, and thereby may reveal processes of deposition otherwise rather difficult to detect.

ACKNOWLEDGMENTS

A large part of the material upon which the conclusions in this paper depend was obtained during cruises of the R/V *Atlantis* of the Woods Hole Oceanographic Institution under the direction of MAURICE EWING of Columbia University. The cruises were sponsored by the National Geographic Society, The Woods Hole Oceanographic Institution and Columbia University (Mid-Atlantic Ridge expeditions). Subsequent coring has been supported by contracts with the Office of Naval Research and the Bureau of Ships, United States Navy. Several valuable suites of cores, and particularly core R5-54, were taken by the U.S.S. *San Pablo* and *Rehoboth* of the U.S. Hydrographic Office. Study of the cores has been conducted at the

Lamont Geological Observatory with financial support of Columbia University, the Office of Naval Research Contarct No. Nonr. 266 (01) and the National Science Foundation Research Grant NSF-G763. The photography was done by R. E. HENNINGHAM and the drafting by M. T. THARP.

The writers are greatly indebted to MAURICE EWING, Director of the Lamont Geological Observatory, and to members of the staff who have given assistance and advice. They are particularly grateful to BRUCE C. HEEZEN, who was directly responsible for taking the A180 series of cores among others, and who kindly advised us regarding the topography of the North Atlantic Basin.

Thanks are due to K. K. WANG of Brooklyn College for assistance in plotting the areal distribution of *Globorotalia truncatulinoides*.

Lamont Geological Observatory Contribution No. 137.

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ADDENDUM

Since submission of this paper for publication J. C. TROELSEN of Universitets Mineralogisk-geologiske Institut, Copenhagen, has kindly called our attention to an article on a similar subject by MILOSLAV VAŠÍČEK. Changes in the ratio of sinistral and dextral individuals of the foraminifer *Globorotalia scitula* (BRADY) and their use in stratigraphy (in Czech with a long summary in English), Sborník ustředního ústavu geologického, vol. 20, paleontology, 1953, Prague. Unfortunately we have not yet been able to procure a copy of this paper.

Deep-Sea Research, 1954, Vol. 2, p. 159. Pergamon Press Ltd., London.

The work of the Joint Commission on Oceanography 1951-54, of the International Council of Scientific Unions

THE early history of the Joint Commission was briefly set out in the Foreword to the first issue of this journal (October 1953). Dr. WISEMAN, President during the period 1951-54, remarked in the same issue (p. 3) that the main purpose of the Commission was to explore the methods of achieving greater international co-operation with the available research facilities for investigating the deep-sea floor.

During its term of office, the Commission discussed the various means whereby it could be useful to the furtherance of international knowledge of deep-sea exploration through the free exchange of views among its members, and it achieved several objects to this end. Realizing the fundamental importance of the Bathymetric Chart of the Oceans, it discussed the possibility of accelerating the rate of production of them and, through a resolution accepted by the Executive Board of the International Council of Scientific Unions, it obtained a grant for the International Hydrographic Bureau of two thousand dollars per annum for five years as from 1954 for this purpose.

In September, 1953, it organized a Symposium at Liverpool University on " the Deep-sea Floor and the History of the Earth," which brought together many scientists who were fundamentally concerned with problems connected with investigations of the deep-sea floor. This well attended symposium was arranged in connection with the British Association's meeting, which immediately followed it, and contributors to the symposium from other countries were invited by the Association to be their guests for their meeting, a gesture which was greatly appreciated.

Our especial thanks are due to the courage of the Pergamon Press in launching *Deep-sea Research*, the initiation of which is probably the greatest achievement of the Commission in promoting the desired international co-operation.

Among other problems considered by the Commission was that of attempting the difficult task of establishing an International Deep-sea Council, or Permanent Bureau, to aid and maintain international relations in problems, both technical, practical and theoretical, concerning deep-sea research. Although the Commission has now served its term of office and has not had it renewed, it has at least achieved some good and has made it clear that a more permanent body is desired by many of those fundamentally concerned with problems of the deep-sea.

The President has asked the writer to join with him in thanking Members and Advisory Councillors for their loyalty, co-operation and interest during the last three years. They can be assured that their work has not been in vain and that it is bound to have influence on future co-operation in deep-sea research.

CAMERON D. OVEY

Department of Geography, University of Cambridge.

LETTER TO THE EDITORS

A plea for Oceanology

(*Received 29th November, 1954*)

OCEANOGRAPHERS seem constantly to be saying that their problems are great, that young men are not coming forward to solve them, and that there is apathy at the Universities.

There is no point therefore in making Oceanography more difficult by the retention of so glaring a misnomer. The word derives from the Greek ωκεανός (outer seas, ocean) and γραφή (writing, drawing, description) and means literally ' ocean description.'

Clearly this meaning no longer embraces the wide range of subjects with which present-day Oceanographers deal. Such activities are more accurately defined by the wider term Oceanology, which again stems from the Greek (λόγος : a word, one who speaks of, or studies; hence λογία: branch of knowledge, science). Oceanology thus means ' Ocean-study ' or science of the oceans.

In this connection it may be useful to consider how far a parallel may be drawn with such terms as geography, geology: petrography, petrology; hydrography, hydrology; seismography, seismology; and even perhaps biography, biology. In each case, whatever may have been the effect of custom and long usage, the former word actually denotes the treatment of a particular facet of the latter – the writing, drawing, mapping, or descriptive aspect. The latter term defines the science as a whole.

The repeated and refreshing use by Dr. A. F. BRUUN of the word Oceanology and its derivative Oceanologist (*Deep Sea Research*, Vol. 2, No. 1), suggests that some members of the Oceanographic profession do recognise the anomaly. It is to be hoped that wider use of those terms may in time lead to their general adoption, and so, conceivably, to a clearer understanding of " Oceanography."

G. P. D. HALL, Commander R.N.

Deep-Sea Research,, 1955, Vol. 2, pp. 161 to 171. Pergamon Press Ltd., London.

Some bathymetric and geotectonic features of the eastern part of the Indian Ocean†

RHODES W. FAIRBRIDGE

Summary—Tectonic relations of the mainland of Western Australia are reflected seawards by the topography of both continental shelf and adjacent deep ocean floor respectively. The basic pattern of the mainland is controlled by the early Pre-Cambrian " grain " (fracture and folding trends). The continental shelf is narrow and rocky where these ancient orogenic lines cross it, and they appear to continue oceanwards in elevations of the deep-sea floor. On the other hand, the Palaeozoic-Mesozoic-Tertiary basins (paraliageosynclines) of the mainland (up to 20,000 feet deep) are matched on the shelf by wide sandy, and atoll-rimmed embayments; and seawards again by oceanic basins approaching 3,000 fathoms in depth. Crustal character of the main eastern Indian Ocean suggests a thalasso-craton (here defined as primary oceanic crust), but these marginal intermediate ridges and basins suggests a common evolution with the continent. Formal names have been given to sectors of the West Australian shelf and the deep-sea floor in the eastern part of the Indian Ocean.

INTRODUCTION

A RECENT study of the Western Australian continental shelf and its sediments by the writer and one of his students (CARRIGY and FAIRBRIDGE 1954) required some consideration of the deep-sea floor in the adjacent parts of the Indian Ocean. No original bathymetric surveys were carried out, but the chart data at present available led to some thought on the geotectonics of the ocean floor and margin; further it was found desirable to apply names to certain bathymetric features which warrant particular nomenclature. Rules laid down by the International Committee on the Nomenclature of Ocean Bottom Features (WISEMAN and OVEY 1953; OVEY 1954) have been adhered to.

The present paper will serve to bring forward some comments on the suspected tectonic significance of the topographic structures delineated, and further, to make available those names in an international journal.

The best available chart of the area concerned is that prepared by VENING MEINESZ (1948) for his latest work on gravity measurements at sea, and here he proposed names for the more outstanding features. The latest edition of the *Carte Générale Bathymétrique des Océans* (sheet A'III) was issued in 1942. A general outline of existing knowledge on the area may be found in SCHOTT (1935).

MAIN TOPOGRAPHIC FEATURES

In another paper (FAIRBRIDGE 1948) it was indicated that the Indian Ocean appears to be divided by the Mid-Indian Ridge into two diverse regions, a western characterized by numerous linear ridges and small basins, and an eastern part marked by a very broad, rather featureless depression (see Fig. 1).

This eastern depression is known as the INDIA-AUSTRALIAN BASIN* (SCHOTT 1935) and occupies approximately 4,000,000 square miles. It is divided in two by an

† See note at foot of page 171.
* Or " Cocos-Keeling Basin," by the British Committee on the Nomenclature of Ocean Bottom Features (Royal Society, Mimeo., 1951).

ENE-WSW series of scattered submarine plateaux, seamounts and atolls (including Cocos-Keeling and Christmas Island) that correspond to a line joining Java and Madasgascar; lying along the western part of the line, that is west of the Mid-Indian Ridge, are the important volcanic islands of Rodriguez, Mauritius and Reunion.

Echo-sounding traces (see, for example, those published by VENING MEINESZ 1948) of the India-Australian Basin show a relatively flat, featureless floor, in marked contrast to the rugged topography west of the Mid-Indian Ridge. An idea favoured by PETTERSSON (1949), KOCZY (1954), and by GASKELL and ASHTON (1954) is that extensive lava flows might explain the flatness, and also the hardness of the bottom. WEYNSCHENCK (1951) suggests that this is a normal deep sea carbonate sediment that has become dolomitized.

It appears unlikely (to the writer) that this horizontality may be explained purely by sedimentation, as ERICSON, EWING and HEEZEN (1952) would for the floor of the western North Atlantic, because the region is far removed, and topographically isolated, from regions of high sedimentation. The evidence deduced by DIETZ (1953) of sediment filling and turbidity currents in the Bay of Bengal, fed by the great rivers of India, is doubted by KOCZY (1954) and in any case cannot be matched by any such profiles or rivers from the arid continental shores of Western Australia. One might expect to find, as in the Atlantic, numerous little sea-knolls in the marginal areas, such as might represent peaks of a rough topography almost " drowned " by sediment. But this is apparently not the case, except in special areas. A guyot-like knoll is found at 400 fathoms just off the edge of the Rottnest Shelf but this feature is on a different scale altogether; it may represent the stump of a Tertiary basalt eruption, as it lies along the trend of several other small plugs in the coastal plain of southwestern Australia. Numerous knolls and seamounts were found by the Swedish Deep-Sea Expedition (*Albatross*, see KOCZY 1954) and two more sea-mounts were found here by the *Challenger* (GASKELL and ASHTON 1954) in the region south of the Java Trench (the " Christmas Rise " here proposed), but again this is a special area, coming under the influence of the tectonism of the Indonesian mobile belt.

NEW FEATURES DESIGNATED

The new subdivisions of the India-Australian Basin have been recognized within a belt 400 to 500 miles off the Australian side of the basin. There now appear to be a number of marginal ridges and basins here. The principal elevations have been designated as follows :

(a) *Leeuwin Sill* (of CARRIGY and FAIRBRIDGE 1954) a low ridge of under 2,000 fathoms depth, connecting the south-western point of Australia, Cape Leeuwin, with the South-West Australian Ridge (of VENING MEINESZ 1948). It trends roughly north and south, and is about 200 miles long. It is termed a " sill " because it forms a partial barrier between the South Australian and West Australian basins.

(b) *West Australian Ridge* (of VENING MEINESZ 1948) is a spur extending north-west from the West Australian mainland from about 30°S in the direction of (but not reaching) the Cocos-Keeling Islands. It is approximately 800 miles long and is almost everywhere less than 2,000 fathoms in depth, along the crest being locally under 1,000 fathoms.

(c) *Exmouth Rise* (of CARRIGY and FAIRBRIDGE 1954) is a broad swell (in tectonic terminology) lying to the north of Exmouth Gulf and north-west of the Pilbara

district of Western Australia. Its axis appears to be NE-SW, that is, parallel to the coast here, measuring 500 miles by 200 miles. It is only partially surrounded by the 2,000 fathom contour being connected to the mainland by a low and broad platform.

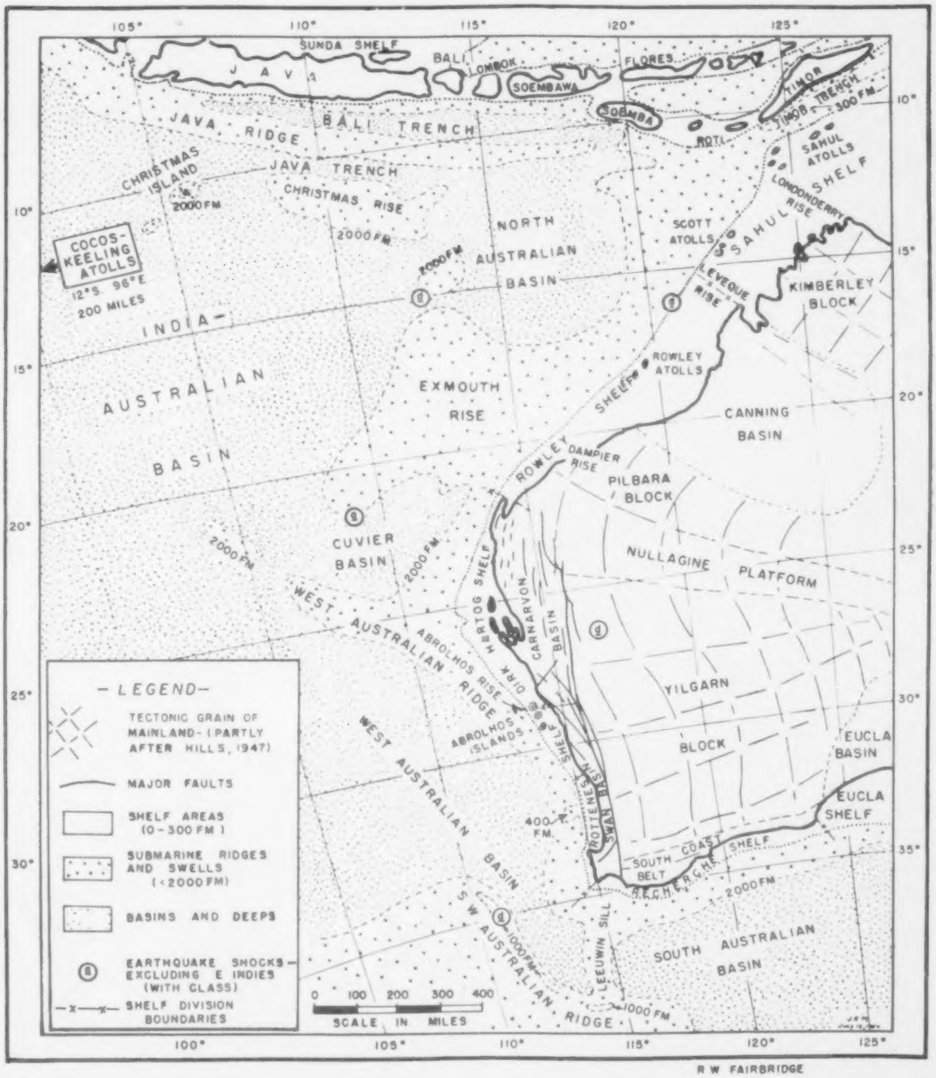

Fig. 1. Bathymetric sketch-map of the eastern part of the Indian Ocean, showing relationships to the tectonic " grain " of Western Australia. Note how the Pre-Cambrian structures of the continent appear to cross the continental shelf and extend into the adjacent deep-sea area; and how the younger basins of the mainland with their broader shelves are reflected off-shore by deep-sea basins.

(d) *Christmas Rise* (now proposed) is a somewhat similar swell almost connected to the Exmouth Rise, but lying to the north and parallel to the Java Trench. It forms, so to speak, an under-developed third arc in the East Indian sequence, but

clearly lacks the mobility and seismicity of the two main arcs (Inner and Outer Banda Arcs). It extends eastwards from near Christmas Island for 300 miles, and may possibly reach as far as 120°E in depths approaching 3,000 fathoms. The occurrence of such recessive " third arcs " is becoming an accepted feature of most contemporary mobile belts.

In contrast to all these elevations which are characterized by linear developments, there remain between them a number of depressions which are sufficiently distinctive to warrant local designation, yet are each more or less connected with the main India-Australian Basin. Whether or not definite western boundaries may ultimately be found must await more detailed surveys. These depressions are :—

(a) *West Australian Basin* (of Vening Meinesz 1948) lies south of the West Australian Ridge, north of the South-West Australian Ridge and is separated by the Leeuwin Sill from the South Australian Basin, a fact that has become apparent only since the publication of Vening Meinesz's map of 1948. The basin is mostly over 3,000 fathoms deep.

(b) *Cuvier Basin* (of Carrigy and Fairbridge 1954), named after Cape Cuvier, 200 miles south of North West Cape, lies between the West Australian Ridge and the Exmouth Rise. It is almost enclosed by the 2,000 fathom contour and approaches 3,000 fathoms in depth.

(c) *North Australian Basin* (of Carrigy and Fairbridge 1954) lies in the V-shaped angle between the East Indies and north-western Australia. It is bounded on the south-west by the Exmouth Rise, on the north-west by a number of slight elevations leading to the Christmas Rise and the southern margin of the Java Trough. On the east it is limited by the Sahul Shelf.

In our sediment studies of the adjacent continental shelves, it has been found convenient to name these too.* From north to south, they are:

(i) *Arafura Shelf* (Krümmel 1897), from Cape van Diemen (Northern Territory) to New Guinea.

(ii) *Sahul Shelf* (of Molengraaff and Weber 1919; restricted by Fairbridge 1953), from Cape Leveque to Cape van Diemen.

(iii) *Rowley Shelf* (Fairbridge 1953), from Cape Leveque to North West Cape.

(iv) *Dirk Hartog Shelf* (Carrigy and Fairbridge 1954), from North West Cape to Abrolhos Islands (29°S).

(v) *Rottnest Shelf* (Clarke 1926) from Abrolhos Islands to Cape Leeuwin.

(vi) *Recherche Shelf* (Carrigy and Fairbridge 1954), from Cape Leeuwin to Israelite Bay (124°E).

(vii) *Eucla Shelf* (Carrigy and Fairbridge 1954), from Israelite Bay to Fowlers Bay, South Australia (132·5°E).

Beyond this point, and still within the bounds of the Indian Ocean (following Schott's limits, 1935), there are several further divisions of the southern Australian shelf, but these have not yet been named.

Most of these shelves are regions of low or interrupted sedimentation (Carrigy and Fairbridge 1954), and this may be partially responsible for the lack of sub-

* An effort has been made to adhere to modern nomenclatorial practice, which requires that whenever possible a geographic name shall be employed in designating bathymetric features. Thus, the Rowley-Sahul Shelves were formerly named " North-west Shelf " (Krümmel 1897); and the writer himself sinned in naming the Rottnest Shelf " West Coast Shelf " (Fairbridge 1950).

marine canyons reported off Western Australia. A single such canyon was suspected by Shepard (1948) off Shark Bay and may correspond to the Pleistocene course of the Gascoyne River; soundings are very sparse, however, and confirmation is needed.

TECTONIC RELATIONS WITH MAINLAND AND SHELF

Geological studies of the adjacent Australian mainland show that it consists essentially of an ancient, Pre-Cambrian shield of approximately 2,000,000 square miles area, which is marginally overlapped by a series of younger basins (" paralia-geosynclines " in the terminology of Marshall Kay 1951; " paralic basins " of Tercier, see discussion in Teichert 1947; named in Gentilli and Fairbridge 1951). These represent broad downwarps of the continent, being now filled with up to 20,000 feet of sediments ranging in age from the Palaeozoic to the Quaternary. Locally these sediments are heavily faulted and gently folded (Germanotype tectonics), but nowhere are they affected by major orogenic compression. The amount of downwarp is of the order of 1 to 4 miles distributed over basins 100 to 400 miles wide. It is apparent therefore that the West Australian Shield is a crustal feature of very great longevity and high stability. Large parts of it have hardly been more than gently warped over a period of over 1,000 million years.

Study of the continental shelves marginal to this continent (Fairbridge 1953; Carrigy and Fairbridge 1954) have disclosed the fact the shelves are broadest and deepest opposite the basins on the mainland, while dominant ridges, platforms or positive blocks in the Pre-Cambrian framework are reflected on the continental shelf by a narrow, shallow character. A geomorphologic reflection of these relations may be seen in the fact that the shelves opposite the mainland ridges, are marked by rocky shores and offshore islands of Pre-Cambrian rocks, while the shelves next to the younger basins are marked by sandy shores, with coral reefs and even atolls near the outer parts of the shelf.

The conclusions drawn from these relations are that the histories of the continental shelves are directly related to the tectonic history of the adjacent continent. There is, incidentally no such thing as the " ideal " continental shelf in Australia (or any other continent) for it may be seen that there are shelves both of accumulation (the theory of Murray 1885) and of erosion (as postulated by von Richthofen 1886), intergrading as compound shelves (as visualized by Buchanan 1887; Fenneman 1902; and Daly 1927), all distributed along one and the same continental margin, which would appear to have experienced a more or less connected structural evolution and been subject to a uniform eustatic history.

A second observation derived from these studies is that the deep-sea basins in turn seem to lie opposite the broad shelves and the continental basins, while the deep-sea ridges lie in the same trends as the Pre-Cambrian structural " grain " of the mainland. From this it may be concluded that *the features of the deep-sea floor are intimately related to those of the continent*, a point recently re-emphasized by Hans Cloos (1948) and by Lees (1953).

It should be stressed that this conclusion refers specifically to the relations between the West Australian Shield and the eastern part of the Indian Ocean and should not be taken as a universal generalization. However, it is true that similar relations have been seen elsewhere, notably between Africa and its adjacent seas. Krenkel (1925) made the earliest observations, and following publications of the detailed

surveys of the *Meteor* Expedition (STOCKS and WÜST 1935), CLOOS (1937, 1948), investigated the geotectonic significance of these continental " felder " being reflected in the pattern of the ocean floor. CLOOS further claimed that these facts provided solid grounds for objecting to the idea of continental drift as envisaged by WEGENER in such regions.

At the same time it is desirable to point out that other sections of the ocean floor, e.g., the main India-Australian Basin, do not appear to possess this basic " felder " pattern of ridges and basins. Notably the central and southern parts of the Pacific Ocean (outside of the Andesite Line and its eastern marginal belt) lacks any such features so far as may be judged from the limited exploration data yet available.

GONDWANALAND PROBLEM

This is not the place for a detailed treatment of the problem of Gondwanaland, that " Atlantis " of the southern hemisphere which SUESS (1904-24) proposed as an explanation for the similarities in the geologic history, fauna and flora of the southern continents. Yet observations on the floor of the ocean separating the present continents are bound to bring up the question.

The present status of this theoretical macro-continent may be expressed as a point of view. Seen through the eyes of an observer residing in one of the southern continents, all the northern land-masses have much in common. In the same way, the southern lands have similarities so striking that SUESS thought that at one time they must have been connected. STILLE's " Norderde," or " Laurasia " of others, has many features which distinguish it from the " Süderde " or " Gondwana " continents. But this does not prove that one or the other was once a continuous land mass ; it merely demonstrates a more or less common geologic history, at the same time, more or less distinct from that of the opposite hemisphere.

Many of the data, originally employed by SUESS, WEGENER, and others to demonstrate the uniformity of Gondwanaland have now fallen into disrepute. Most of the zoogeographic anomalies are now explained differently; the *Glossopteris* plants are now found to have winged spores, and so on.

Nevertheless, considerations of the geological history of the Indian Ocean suggest that its borderlands were continental for long periods. Two important gulfs, the Malgashe or Madasgascar Gulf on the west and the Westralian Gulf on the east, appeared during late Paleozoic times and widened during the Mesozoic. The first continuous marine connections around South Africa appeared during the Cretaceous with numerous small coastal transgressions. However, the first evidence of any close link from the west around the margin of southern Australia did not come until the Tertiary; TEICHERT (1951) recognizes Permian faunistic connections between Western Australia and Tasmania, but there is no evidence as to the route or location of this marine link.

The Mesozoic marine faunal developments of the Malgashe Trough, peninsular India and Westralian Trough, for similar environments, are naturally analogous, but they are sufficiently distinct that they may best be epxlained as being then as far apart as they are now. There is the granitic nature of the Seychelles (BAUER 1898) and possibly continental foundations of other parts of the north-western Indian Ocean (GLENNIE 1936) that speak against drift in that region.

The conclusion has therefore been reached by STILLE (1944, 1948) and also by

the writer (1948) that the Indian Ocean is a " new ocean," one which owes its origin (at least in part) to the break-down of former continental crustal elements.

GEOTECTONIC CONSIDERATIONS

Stille believed that the Indian Ocean was entirely a " Neuozean " (new ocean), but subsequently the writer's bathymetric-tectonic studies suggest that much of the large eastern basin may be underlain by primary oceanic crust (or " thalasso-craton "). Geological support for this concept has come in recent years from the discoveries of extensive Ordovician, Devonian and Carboniferous marine sediments in Western Australia (Teichert 1950; Guppy and Opik 1950), thus considerably antedating the Permian-Mesozoic marine history of the western side of the Indian Ocean. Such repeated Palaeozoic transgressions suggest a Paleozoic oceanic region in the east rather than a mere epicontinental gulf.

The term " thalasso-craton " (derived from the Greek *thalassa* = ocean; *kratos* = mastery or strength) is proposed by the writer to cover the concept of a part of the earth's strong, semi-rigid crust (" craton ") that underlies the primary or permanent ocean basins. This distinguishes such regions from the " hedreo-cratons " (of Kay 1951) that occupy the semi-rigid continental masses. These two distinct divisions of the earth's crust were first designated by Stille (1934, 1944) as *Hochkratone* and *Tiefkratone*, but to avoid using terms of mixed linguistic roots, it seems best to employ the equivalents " hedreo-craton " and " thalasso-craton."

Stille accepted the idea of the permanence of continents and oceans, only with reserve, however, recognizing that marginal parts of the hedreo-craton could subside in later cycles, being downwarped or downfaulted irregularly to oceanic depths. This process he named " Regeneration." Such a concept seems to fit well the data here presented for the marginal areas of the eastern Indian Ocean.

In complete contrast to these more rigid units, are the Mobile Belts (" Orogen " of Kober) exemplified by the Indonesian Island Arcs on the northern side of our area. With their history of high mobility, seismicity, and vulcanicity, their vertical movements are of very different nature. Such belts one conceives as the granite-cored geosynclines of the future.

The regenerated areas may be regarded as transitional and of only semi-mobile character. It seems appropriate to distinguish them as the " Intermediate Areas." Regenerated sections of the ocean, as shown above, seem to pass without abrupt boundary into the semi-mobile basins of the continent. Where visible and available for direct study, it is possible for the stratigrapher to classify such basins amongst those geosynclines which evolve tectonically with intermediate type structures (Saxonian or Germanotype of Stille), but which do not reach the degree of mobility that results in granitization or plutonic injection.

The term " parageosyncline " (Stille) is appropriate to such basins. It was first used by Schuchert (1923) in a somewhat different sense, but was never adopted into the literature. The term was redefined by Stille (1935, 1936) to cover all those basins of sedimentation with semi-mobile to semi-rigid (i.e. well consolidated) basements, characterized by Saxonian or " Germanotype " tectonics; thus they are in in contrast to orthogeosynclines with their highly mobile basements and "Alpinotype" tectonics. Kay (1942) has discussed these terms, and introduced (1951) a series of new ones (exo-, zeugo-, auto-, paralia-, taphro-geosyncline, etc.) to cover

the varied types of basin with semi-rigid basements. He did not adopt " parageosyncline " as a general term for them, out of respect for SCHUCHERT's priority. However, as a group term is urgently needed here and SCHUCHERT's usage was never employed by geotectonicists, there is a strong case for adopting STILLE's term, which is already widely employed in Europe.

It is apparent, therefore, that if the marginal parts of the Indian Ocean have been formerly continental, they must have subsided. They must accordingly occupy the role of parageosynclines, a complex belt of intermediate mobility lying midway between the highly rigid thalasso-craton of the Indian Ocean and the equally rigid hedreo-craton of the Australian continent. To the north, the thalasso-craton is separated from the hedreo-craton of South-East Asia by the orthogeosynclinal Mobile Belts of the East Indies. In both cases the oceanwards transition from the belts of increased mobility into the thalasso-craton appears ill-defined and gradual.

By analogy with geologically explored geosynclinal belts, it seems probable that both orthogeosynclinal and parageosynclinal belts possess a basement of inhomogeneous sialic character. In contrast the thalasso-cratonic basement, judging from the nature of associated volcanic rocks, must be essentially simatic. Geophysical data may shed some light on this aspect in the Indian Ocean, as may be seen from the next section.

GEOPHYSICAL DATA

Outside of the East Indian island arcs and associated oceanic trenches, the natural seismicity of the eastern part of the Indian Ocean is of a very low order. This is equally true for the adjacent parts of continental Australia. GUTENBERG and RICHTER (1949) lists only four ocean or shelf-margin shocks for the entire area under discussion (excluding, of course, the East Indies), and there is no change in the 1954 edition. Accordingly, local earthquakes may be of little help in determining the nature of the earth's crust just here.

Long-range determinations of Rayleigh-type waves may, however, be instructive. EWING and PRESS (1952) have shown that Rayleigh waves emanating from an earthquake in the Solomon Islands and recorded at a series of points on a great circle around the earth would pass through Australia, the Indian Ocean, South Africa, the Atlantic, North America and the central Pacific. When allowance is made for the known continental sectors of the course, the oceanic portion could be accounted for by assuming a water layer resting on a homogeneous simatic rock of 7·9 km/sec compression velocity. This is considered a fair mean for the thalasso-craton, which is known to be underlain by a layer of 6·8 resting at the Mohorovicic discontinuity on one of 8·1 km/sec. This would imply that *all* ocean sectors along this great circle course were essentially thalasso-cratonic. However, owing to the scale involved and the single example used there still seems room for a certain proportion of ocean of intermediate character (that may have been formerly continental).

Some very interesting conclusions have also been reached from consideration of the earthquakes emanating from the Mid-Indian Ridge. GUTENBERG and RICHTER have long regarded this as part of a circum-African ring, continuous via the Crozet Ridge with the Mid-Atlantic Ridge. The topography and geology of the ocean floor to the interior, i.e. African side of that ring suggests more a continental origin. As

the present writer noted above the exterior, certainly the eastern part (i.e. in the Indian Ocean) suggests a thalasso-craton.

Results are still incomplete but a study of P-waves originating in the Mid-Indian Ridge earthquakes by Father POISSON (1950) at the Tananarive (Madagascar) seismological station, showed several seconds delay in reaching the African shore than in getting to the station in Western Australia. This interesting anomaly, if confirmed, would imply a notably different crustal structure east and west of the Mid-Indian Ridge, is as already implied by the topography (ROTHÉ 1951, 1954).*

Up until the present time, the only oceanographic expedition into the area employing seismic refraction surveys, has been that of the H.M.S. *Challenger* (II) in 1952 (see preliminary notes by GASKELL 1954; GASKELL and ASHTON 1954). This traverse was restricted to the northern part but serves to show the existence of a thalasso-cratonic crust. This is what GASKELL calls a "Type A" crust, characterized by a deep Pacific type profile, that is, about ½ km of sediment, 5 km of crust 6·5 km/sec velocity (generally regarded as indicating a simatic composition), reaching the Mohorovicic discontinuity and 8·1 km/sec velocity at about 11 km below sea-level.

A number of oceanographic gravity stations were established in 1935 by VENING MEINESZ (1948) on the Dutch submarine K-XVIII. Most important for our area was the traverse made following the western margin of Australia from Fremantle-Java, crossing most of the structures described in the first part of this paper. VENING MEINESZ has remarked on the universality of a remarkable gravity anomaly over continental margins, but this traverse is parallel to that margin. Notable negative isostatic anomalies were determined at stations 717 and 716 (over the Pilbara Rise), while a positive swing was established at station 715 over the Cuvier Basin. Their course was set too close to shore in the latitude of the West Australian Ridge, so no indication of this was recorded. It was observed, however, that an E-W profile over the West Australian Basin presented the usual deep-sea picture of no appreciable anomaly.

CONCLUSIONS

The conclusion we may reach from these, admittedly sparse, data is that the crust beneath the Indian Ocean is not all of one character, being marginally continental in origin. Further, in contrast to the belief of this writer in 1948, the ocean is not all of "juvenile" origin, but has a notable "core" of great antiquity, a thalasso-craton of Pacific character. It does not extend right to the margins of the Western Australian Shield which would appear to have been broken down in the course of post-Cambrian time along a belt up to 400 or 500 miles wide.

In considering a thalasso-craton of Pacific character, it is alomst inevitable to think at the same time of island arcs. In this instance it becomes understandable that the Burma-East Indian arcs should *face* the north-eastern Indian Ocean in its deepest sector.

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* GUTENBERG and RICHTER (personal communication) have indicated to the writer that these results are very uncertain owing to inaccuracies of epicentre location, so the case must be marked "unproven" as yet, (R.W.F.)

VENING MEINESZ, H. H. HESS, J. TUZO WILSON, J. P. ROTHÉ, F. PRESS and others. Also the facilities provided by ROGER REVELLE at the Scripps Institution, when the writer was visiting the United States with the assistance of a FULBRIGHT Grant.

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⁂ Unfortunately this paper went into print before the British National Committee on the Nomenclature of Ocean Bottom Features, to which DR. FAIRBRIDGE had addressed himself for an opinion, had met to consider the naming of the deep-sea features to which he refers above. The Committee met on 26 November and came to the conclusson that the names Leeuwin Sill, Christmas Rise, West Australian Ridge, Cuvier Basin, North Australian Basin, West Australian Basin and Exmouth Ridge, would require further consideration.—C.D.O.

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The significance of organic phosphorus determinations in ocean waters*

BOSTWICK H. KETCHUM, NATHANIEL CORWIN and D. JEAN KEEN†

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Summary—1. Total phosphorus can be measured by the Harvey method with an accuracy of about ± 5% (Standard deviation). The blank obtained using reagent grade chemicals without special purification is about 0·2 μgA/L.

2. Organic phosphorus is determined by the difference between the inorganic and the total phosphorus concentrations. Unless this difference exceeds 10% of the concentration it cannot be considered significant.

3. Analysis of almost a thousand samples from the equatorial Atlantic Ocean on which both inorganic and total dissolved phosphorus were determined indicates :

(a) that 95% of the surface water samples contain significant amounts of dissolved organic phosphorus.

(b) that the frequency of samples showing significant amounts of dissolved organic phosphorus decreases with depth and with the content of inorganic phosphorus.

(c) that at depths greater than 1,000 metres no measurable amounts of dissolved organic phosphorus are detectable by the present methods.

INTRODUCTION

ORGANIC phosphorus in sea water may be measured by the difference between the total phosphorus and the inorganic phosphorus content. The inorganic phosphorus must be measured as soon as possible after the removal of the samples from the sea but the total phosphorus samples can be stored and measured in the laboratory. Very few determinations of total phosphorus have been made, although it has been demonstrated that the concentration of organic phosphorus may exceed the concentration of inorganic phosphorus in the surface waters (KALLE, 1935 ; REDFIELD, SMITH and KETCHUM, 1937 ; HARVEY, 1948 ; HANSEN and ROBINSON, 1950 ; ARMSTRONG and HARVEY, 1953). HARVEY'S (1948) total phosphorus method is less laborious and time consuming than earlier methods, and it has been used on a routine basis in this laboratory for about three years. Samples can be obtained on any oceanographic cruise without the necessity of personnel trained in intricate chemical methods and they can be stored for periods of up to two years without measurable change in total phosphorus. This method should greatly facilitate studies of the distribution of phosphorus in the oceans.

During a joint cruise by the *Atlantis* and *Albatross* III in the equatorial Atlantic Ocean in 1952 nearly a thousand samples were collected on which both inorganic and total phosphorus determinations have been made. Since the organic phosphorus was frequently represented by a small difference between two relatively large values,

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†Present Address, U.S. Navy Hydrographic Office, Wash., D.C.

it was found necessary to evaluate the methods statistically in order to determine whether or not the differences were significant.

This paper presents the results of the evaluation of the accuracy of the Harvey method for total phosphorus determinations, and of the method used on shipboard for the determination of inorganic phosphorus. The results indicate that about 95% of the surface water samples obtained from the equatorial Atlantic Ocean contained significant amounts of dissolved organic phosphorus. In water deeper than 1,000 metres the concentration of dissolved organic phosphorus was too small to be distinguished by the present methods.

TOTAL PHOSPHORUS

1. *Method :*

The method as described by HARVEY (1948) has been altered only slightly. It is briefly outlined below, but reference to the original is recommended.

1. Samples of sea water of about 200 ml. are placed in 8 oz. bottles with plastic screw caps and rubber liners. These bottles are carefully cleaned beforehand by scrubbing the walls and bottom with a rubber policeman and 10% HCl and are then rinsed thoroughly with tap water and 5 or 6 times with distilled water. They need not be rinsed with the sea water sample. Samples have been stored in the dark for periods up to two years without measurable change in total phosphorus.

2. When analyzed in the laboratory, 1 ml. of concentrated HCl is added to the bottle, the walls and bottom are vigorously scrubbed to remove any adhering bacterial film, and a 50 ml. sample is transferred by volumetric pipette to a 125 ml. " Vycor " flask.

3. Two ml. of 38% H_2SO_4 and 4 drops of saturated aqueous solution of Na_2SO_3 are added to each flask, which is covered with a 50 ml. " Pyrex " beaker.

4. The samples are digested in a steam autoclave for five hours at about 38 lb./sq. inch. pressure (140°C).

5. After cooling, each sample is diluted to 100 ml. with distilled water, transferred to a 250 ml. " Pyrex " flask and 2 ml. of 2·5% amonium molybdate is added. A measurement of light absorption is made with the photoelectric colorimeter described by FORD (1950) using a tube length of 29 cm and red light filters (Corning 2408). This gives a measure of the turbidity and is the zero reading for each determination.

6. Four drops of a stannous chloride solution containing 0·2 g of $SnCl_2 . 2H_2O$ in 25 ml. of 10% HCl are added. This solution is made fresh each day.

7. The colour developed is read with the photoelectric colorimeter within 5-10 minutes after addition of the $SnCl_2$, using the same light filter and tube as were used in determining turbidity (paragraph 5).

8. One or more blanks are digested with each set of analyses. Distilled water is treated in exactly the same way as the samples (2 to 7 above).

9. The photoelectric colorimeter is calibrated by analyzing samples to which inorganic phosphate has been added to sea water in concentrations ranging from 0-3 μg atoms P/litre. The sea water used is surface Sargasso Sea water which is low in total phosphorus and usually ranges from 0·25 to 0·75 μg atoms P/litre. A linear relationship is found between concentration due to added phosphorus and reading within these limits.

The colour developed is temperature dependent, increasing about 1% per degree centigrade (see WOOSTER and RAKESTRAW, 1948). Our analyses have been conducted at ambient room temperatures and the calibrations have been made under the same

conditions. The effect of temperature variations is included in the standard deviation of the method which will be discussed below.

ARMSTRONG and HARVEY (personal communication) have detected dissolution of phosphate from their glass bottles during storage. They report solution of less than 0·02 μg atoms/litre in one week from " good " glass and between 0·2 and 0·4 μg atoms/litre in one week from " poor " glass. We have been unable to detect measureable increases of phosphate during storage in the dark for periods up to two years, though a considerable increase in turbidity of the sample sometimes occurs when stored after the addition of the HCl. Analyses indicate that an increase in silicate is not responsible for this increased turbidity. We have not tested various types of glass for storage of samples, but our results indicate that the Duraglass bottles we have used are satisfactory.

The substitution of " Pyrex " for " Vycor " flasks during the digestion is unsatisfactory, owing to large blanks and erratic results. This confirms HARVEY'S (1948) conclusion that silica glass containers are essential for the digestion.

Two types of steam digesters have been used. The first was a high pressure vertical model (ten inches in diameter by eleven inches deep) (Eimer and Amend 1-811) in which only 16 samples could be digested daily. We now use an American Sterilizer Co. horizontal steam autoclave (20 in. in diameter by 36 in.) which has been modified with a bypass so that condensed steam in the chamber is returned directly to the gas fired steam boiler. In this apparatus over a hundred samples can be digested at once. We have found it convenient to digest about sixty at a time. The analysis of these can be completed on the following day while additional samples are digesting. The calibrations and results in these two digesters have been identical.

The recovery of organic phosphorus from a standard solution of 5 adenylic acid (adenosine 5 phosphoric acid) containing 1·01 μg atoms/L was tested. After digestion by the Harvey method three replicate samples gave recoveries ranging from 1·0 to 1·02 μg atoms/L.

The recovery of total phosphorus from a culture of *Nitzschia Closterium* was also tested. These samples were diluted ten-fold with distilled water before digestion. The original cultures contained 3,000 cells per millilitre and 13·8 μg atoms P/L. When the count had increased to 390,000 cells per millilitre the inorganic phosphorus in solution was 5·5 μg atoms/L, and the total phosphorus recovered was 13·6 μg atoms/L or 98·5%. With a cell count of 1,150,000 per millilitre, the inorganic phosphorus had decreased to 0·07 and the total phosphorus was 13·4 μg atoms/L or 97%. As will be shown below both of these recoveries are within the expected error of the method of the analysis.

2. *Comparison of Methods* :

Comparison between HARVEY'S (1948) method, and that described by REDFIELD *et al.* (1937) has shown that both yield similar results. Individual analyses, however, did not always agree as well as could be wished, HARVEY'S method giving results ranging from 0·75 to 1·40 times the result obtained by the earlier method. This ratio was calculated for analyses done by both methods on 43 separate samples of sea water. The mean ratio was 1·04 with a standard deviation of 0·143 ($\pm$ 14%). The replicate results obtained with HARVEY'S method were superior to the replicates by the method of REDFIELD *et al.*, and it appeared that much of this variation was

inherent in the older method. The reproducibility of the Harvey method will be discussed below.

These results indicated that identical amounts of total phosphorus were determined by the two methods. Because of the greater simplicity of the Harvey method it has been used exclusively by this laboratory since 1952.

3. *Reagent Blanks :*

The average of all reagent blanks determined between July, 1952 and December, 1954 are given in Table I. The results for each year are presented separately, since there has been a gradual improvement in the value. It should be pointed out that reagent grade chemicals are used throughout, and that no special purification of reagents has been attempted, since it was desirable to place the entire method on as routine a basis as possible. We have used "Baker Analyzed" Reagent grade Sulphuric and Hydrochloric acids, and Merck Reagent grade Sodium sulphite, Ammonium molybdate and Stannous chloride.

Table I

Total phosphorus reagent blanks obtained using the HARVEY *method.*

	1952	1953	1954
No. of analyses	60	125	216
Mode, μg atom P/L	0·33	0·23	0·18
Mean, μg atom P/L	0·36	0·27	0·22
Standard deviation μg atom P/L	0·10	0·07	0·11

The blank obtained during 1954 was 0·22 μg atoms P/litre with a standard deviation of 0·11. The distribution curves for the blank determinations are skewed toward the high values, as is indicated by comparison between the mode and the mean values. Small chance contaminations are difficult to avoid when working with such low concentrations. All determined values have been included in the data in Table I, although some of them were obviously contaminated and were not used in the actual calculation of total phosphorus. For example, the following blanks were obtained during one series of analyses : 0·63, 0·31, 0·32, 0·31, 0·31. The high value in this group was not used for the calculation, but it is included in the data in Table I. If these obviously high values are eliminated, the mean value for 1953 would be 0·25 and for 1954, 0·206. The elimination of these unusually high values does not eliminate the skew towards the high values, but it appears that they occur infrequently enough so that they have not substantially altered the mean blank value presented.

4. *Reproducibility of the Harvey Method :*

During the period January, 1953 – April, 1954, twenty-one calibrations of the photoelectric colorimeter were made. These permit an evaluation of the reproducibility of the method. An example of a single calibration is shown in Fig. 1. The factor to convert the photometer readings (in arbitrary units) to phosphorus is calculated as follows :

$$\frac{\text{Added } P}{R - R_s} = \text{factor}$$

in which R is the reading obtained for the standard solution and R_s is the reading obtained for the sea water used, which includes the reagent blank and any phosphorus present in the sea water. For this calibration the average of the factors for all samples was $8{\cdot}48 \times 10^{-3}$ or one photometer unit was equal to 0·00848 μgAP/L. The standard deviation was $\pm 0{\cdot}50 \times 10^{-3}$ (5·9%).

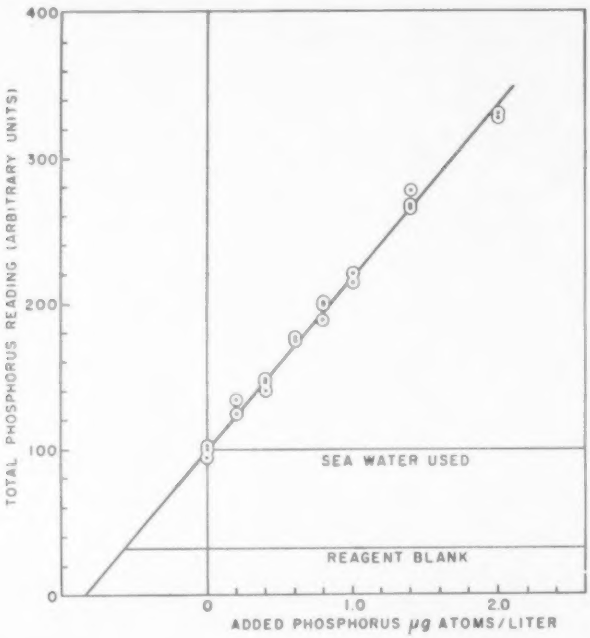

Fig. 1. Example of the calibration of the photometer for the determination of total phosphorus by the Harvey method.

In all, 297 standard solutions are included in the 21 calibrations, and for each of these solutions the factor relating the photometer reading to concentration has been calculated. The standard deviations within each calibration, and the group standard deviation for all of the calibrations performed during this period have been determined. The standard deviation most frequently found for the individual calibrations was 4-5%, though the range was from 2·4 to 11·6%. The average factor for all of the determinations (in arbitrary units) was $8{\cdot}49 \times 10^{-3}$, with a standard deviation of 5·14%. This standard deviation includes changes in reagents and in the photometer over a period of almost two years, as well as the random variations which would be expected within each calibration experiment.

It was mentioned above that the standard deviation of the comparison between the HARVEY and the REDFIELD, SMITH and KETCHUM method was 14%. Since the HARVEY method can be reproduced with an accuracy of about 5%, it would appear that much of the variation found in the comparison can be attributed to the older method. However, these were among the first samples analyzed by the HARVEY method, and it is not certain that the reproducibility of this method was as good at that time as it is now after three years of experience.

INORGANIC PHOSPHORUS

The inorganic phosphorus must be measured at sea at the time of collection to avoid biological changes. The method has been described by WATTENBERG (1937), WOOSTER and RAKESTRAW (1951) and ROBINSON and THOMPSON (1948). The colour developed was measured in the photoelectric colorimeter using a red light filter (Corning 2408) and a cell with a 29 cm light path for concentrations less than 1·0 μg AP/L and a cell with an 8 cm light path for higher concentrations.

The calibration of the photometer was made by adding known amounts of inorganic phosphorus to surface sea water containing little inorganic phosphorus. This procedure automatically compensates for the effect that sea salts have upon the intensity of colour developed. The accuracy of the determination of inorganic phosphorus was evaluated in the way described above for total phosphorus, with the results shown in Table II. The photoelectric colorimeter used on *Atlantis* was the same as that used in the laboratory for both inorganic and total phosphorus determinations. The differences in the factors obtained on *Atlantis* and *Albatross III* results from a different scale on the two instruments which were otherwise identical.

Table II

Variation in the determination of inorganic and of dissolved organic phosphorus.

Source of data	Concentration range	Cell length (cm.)	No. of standards	Factor $\times 10^3$	Standard deviation inorganic %	organic* %
Atlantis	0–1·0	29	10	3·68	6·7	8·4
	>1·0	8	20	12·4	9·3	10·3
Albatross III	0–1·0	29	27	8·0	8·4	10·0
	>1·0	8	20	29·3	8·9	10·6
Laboratory	0–1·0	29	92	3·54	7·6	—

* Obtained by $\sqrt{\sigma_1^2 + \sigma_2^2}$ where σ_1 is the standard deviation of the total phosphorus determination (5·14%) and σ_2 is the standard deviation of the inorganic phosphorus determination.

DISSOLVED ORGANIC PHOSPHORUS

The dissolved organic phosphorus is the difference between the total dissolved and the inorganic phosphorus. The accuracy with which it can be measured depends upon the accuracy of both methods. The combined standard deviation of the two methods is included in Table II. Unless the differences between the total and inorganic phosphorus determinations exceeds 10% of the measurement it cannot be considered significant. Actually almost a third of the random differences may be expected to lie outside the $\pm$ 10% limits, and about 5% may be expected to exceed $\pm$ 20% even though no organic phosphorus is present in any sample. Within these limits, negative differences should be found as frequently as positive differences.

Arsenic present in sea water as arsenate is included in the inorganic phosphorus determination, but is reduced and not included as total phosphorus. Consequently the amount of organic phosphorus may be underestimated by this method. However, the magnitude of this error is small and would produce an insignificant difference in most samples. GORGY, RAKESTRAW and FOX (1948) report arsenate contents of 0·03 to 0·07 μg atom/litre, and ROBINSON and THOMPSON (1948) conclude that the effect of arsenate on the determination of inorganic phosphorus is negligible for sea water containing more than 1 μg atom P/litre.

Both inorganic and total dissolved phosphorus were determined on 991 water samples collected at 94 stations by the *Atlantis* and *Albatross III* during a cruise to the equatorial Atlantic Ocean in 1952. The particulate matter in the water was removed by filtration on shipboard by the method described by REDFIELD, SMITH and KETCHUM (1937). The location of the stations is given in Fig. 2.

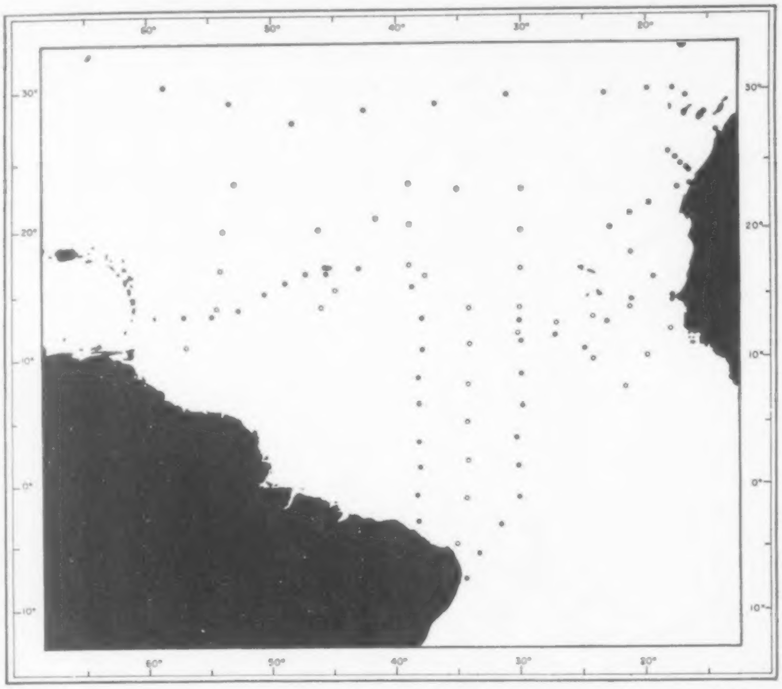

Fig. 2. Location of the stations occupied by *Atlantis* (●) and *Albatross III* (○) at which inorganic phosphorus and total dissolved phosphorus were determined.

When the total phosphorus analysis was completed the results were compared with the inorganic phosphorus concentrations. This was done by plotting the total phosphorus reading (corrected for reagent blank) against the inorganic phosphorus as measured on shipboard. The line determined by the most recent calibration data, and the $\pm$ 10% accuracy limits were drawn. One set of data treated in this way is shown in Fig. 3. Practically all of the samples which contained less than 1·0 μg atoms P/litre showed positive and significant differences between the total and inorganic phosphorus contents. This difference is attributed to dissolved organic phosphorus. Several of the samples containing more inorganic phosphorus also showed positive differences, but these were all within the expected errors of the methods and cannot be considered significant. One of these samples gave much less total phosphorus than had been found originally as inorganic. A recheck of this sample gave the analysis indicated by the special symbol. Presumably the bottle storing this sample was not adequately scrubbed before the aliquot was withdrawn for analysis.

The samples to be rechecked were selected as those containing more than 1·0 μg atoms P/litre in which the indicated total phosphorus differed from the inorganic

by more than $\pm$ 10%. Some samples were selected for rechecking at random, and these included some of the samples containing the smaller amounts of phosphorus. Sixty-three of the *Atlantis* samples were rechecked with the following results : of 31 in which the total phosphorus was less than the inorganic, nine remained in this group, and 19 increased so that the difference did not exceed $\pm$ 10% ; of 22 samples selected with positive significant differences, fifteen remained in this group and seven decreased so that the difference did not exceed $\pm$ 10% ; of ten samples which were originally within the $\pm$ 10% limits, seven rechecks remained in this group, two decreased and one increased. Although some of these samples were stored for more than a year between the two determinations of total phosphorus, and as much as two years after the measurement of inorganic phosphorus, there is no evidence for a consistent increase which could be attributed to solution of phosphorus from the glass.

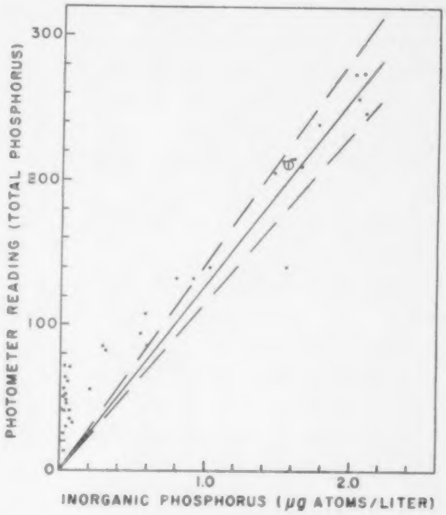

Fig. 3. Relation between the photometer readings for total dissolved phosphorus and the inorganic phosphorus for samples obtained on *Atlantis* stations 4983, 4985, 4986 and 4987. These stations were occupied March 30th to April 2nd, 1952, and the total phosphorus was analyzed on March 27th to April 1st, 1953.

The frequency of significant positive differences between total and inorganic phosphorus (organic phosphorus) and of insignificant and of negative differences is

Table III

Percentage of water samples from the equatorial Atlantic Ocean showing negative, insignificant and positive differences between total and inorganic phosphorus concentrations.

Inorganic Phosphorus (μg atoms P/L)	*No. of samples*	*Total minus % of inorganic phosphorus samples* (−)	$\pm$ 10%	(+)
0·00–0·5	370	0·8	4·3	94·9
0·51–1·0	55	0	32·8	61·8
1·01–1·5	125	1·6	76·8	21·6
1·51–2·0	259	1·5	88·0	10·5
> 2·01	182	1·1	92·3	6·6

shown in Table III for the comparison samples obtained on the *Atlantis* and *Albatross III* cruises in 1952. The observations have been separated into groups depending upon the concentration of inorganic phosphorus in the water. The depths at which these concentrations occur is quite variable, since the low nutrient water extends to several hundred metres in the northern part of the area, while it is limited to less than

100 metres near the equator. The concentration grouping, however, helps to identify the location of the water in relation to the ecological system.

About 95% of the water samples containing low inorganic phosphorus concentrations also contained significant amounts of dissolved organic phosphorus. This proportion decreased with increasing phosphorus concentrations, so that at the highest concentrations less than 10% of the samples showed significant amounts of organic phosphorus. Most of the differences observed among the samples containing more inorganic phosphorus than 1·0 μg atom per litre were within the $\pm$ 10% limits of error. At all concentrations, very few negative differences exceeding the 10% limit were found.

One of the difficulties in deciding whether the deep water, which contains the greater amount of inorganic phosphorus, also contains organic phosphorus, is that the inherent errors of the method eliminate positive values up to 10% of the concentration. As the concentration increases, the ability to identify larger and larger quantities of organic phosphorus by difference is lost. The question arises : are the low frequencies of organic phosphorus in the deeper waters an artifact produced by the errors of the method, or does this water really contain little or no organic phosphorus? No final answer can be given until our methods of analysis improve substantially.

The following further breakdown of the data in Table III is pertinent to this question. Nearly 50% of the surface (0–·5 μgAP/L) samples, contained dissolved organic phosphorus in concentrations greater than 0·25 μgAP/L. Such concentrations would be outside the limits of error of the method for practically all of the deep water samples, and would be identifiable if present. It is certain, therefore, that organic phosphorus occurs at a greatly decreased frequency in the waters containing the higher concentrations of phosphorus.

Of the thirty-nine samples containing more than 1·5 μg atom P/litre and significant amounts of dissolved organic phosphorus, twenty-six were obtained at depths of less than 1,000 metres and are not pertinent to the question. Two hundred and fifty-nine comparison samples were obtained from corrected depths greater than 1,000 metres. Only thirteen of these (5%) gave positive differences exceeding one standard deviation. Statistically this proportion of the samples could be expected to give differences greater than plus or minus two standard deviations, ($\pm$ 20%), but only five of these thirteen samples (2%) gave differences this large.

It can be concluded, therefore, that the waters deeper than 1,000 metres in the equatorial Atlantic Ocean contain little if any organic phosphorus. Only thirteen of our samples gave positive results, and these can be attributed to chance errors in the methods of determination.

DISCUSSION

The advantages of the HARVEY method of determining total phosphorus in sea water include the facts that large numbers of samples can be handled by a routine procedure and that the samples can be collected on oceanographic expeditions by people who are not trained in intricate chemical methods. Our present procedure permits analysis of about 250 samples each week, and the capacity of the digester is enough so that the number of analyses could be doubled by providing an additional analyst to complete the photometry. The analysis can be performed with an acceptable accuracy for a colorimetric determination, and it is our experience that the accuracy of total

phosphorus analyses conducted in the laboratory exceeds the accuracy of inorganic phosphorus analyses conducted on shipboard.

The Harvey method gives results identical with the method of Redfield, Smith and Ketchum (1937). It has not been compared to the perchloric acid method described by Hansen and Robinson (1953). Neither of these two methods, however, provide the simplicity and possibility of conducting large numbers of analyses on a routine basis comparable to the Harvey method.

It would be desirable to have inorganic phosphorus determinations as well as total phosphorus determinations on the samples. It has been obvious in recent years, however, that there are not enough oceanographic chemists to go to sea on every expedition and the total phosphorus samples can be collected even when no chemist is aboard. Total phosphorus is a more conservative property of the water than is the inorganic phosphorus since it is not subject to as great seasonal changes. It differs from other conservative properties only in the gravitational effects on the particulate matter. Armstrong and Harvey (1950) have used total phosphorus as an index of the potential fertility of a water mass, and as a characteristic of different water masses in the English Channel. Soule *et al.* (1954) have used total phosphorus to identify different water masses in the north Atlantic Ocean.

From our results in the equatorial Atlantic Ocean it is apparent that the total phosphorus will be found in greater concentrations than inorganic phosphorus in the surface waters. This makes comparison of total phosphorus with older determinations of inorganic phosphorus somewhat difficult. In water deeper than 1,000 metres, however, the total phosphorus results should not differ significantly from results of earlier measurements of inorganic phosphorus. The study of the phosphorus content of the deep waters of the oceans will, therefore, be greatly facilitated by the use of this method for determining total phosphorus

Woods Hole Oceanographic Institution.

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Oxygen-density relationships in the western North Atlantic

F. A. RICHARDS and A. C. REDFIELD[*,†]

(*Recieved January* 1955)

Summary—A distinctive correlation between oxygen content and sigma-*t* has been shown to exist in the Sargasso Sea. Waters of the Caribbean Sea, Yucatan Channel and Straits of Florida are anomalously lower in oxygen. Similar oxygen anomalies along the supposed course of the Gulf Stream can be used to delineate its right-hand boundary and to trace water of southern origins to as far as 43°W. longitude. The distribution of oxygen anomalies across the Gulf Stream shows that water of southern origins is present in highly variable amounts, that it is present in the various currents and counter-currents, and that these currents are materially related and do not represent merely the transfer of momentum from southern sources.

SALINITY-temperature correlations distinguish the Gulf Stream from Slope water, but not from the Sargasso Sea, and in the past either inferred or measured motion has been used to dilineate the right hand limit of the Gulf Stream. No method of tracing the physical continuity of the actual moving water has been available. The oxygen content of the upper layers in the Gulf Stream is characteristically less than that of Sargasso Sea water of the same density, and can be used to trace its continuity from the Caribbean to at least 61°W. longitude.

ROSSBY (1936), showed that the oxygen-salinity correlation in the Sargasso Sea is different from that in the Yucatan Channel-Florida Straits region, and that this difference is distinct for some distance along the course of the Gulf Stream. He showed that the lowest oxygen concentrations emanate from the Straits of Florida, and that a secondary tongue in which the minimum values are somewhat higher enters the system from the Antilles Current[‡]. We have found that the oxygen content of the shallower layers is more distinctive of Caribbean waters than is that of the oxygen minimum layer, with which ROSSBY's treatment was concerned.

In order to use the oxygen content to distinguish the water masses in question, the correlation between the oxygen concentration and sigma-*t* of Sargasso Sea water has been defined, and anomalies from this correlation have been examined. Sigma-*t* was chosen as a correlative because surfaces of equal sigma-*t* are of approximately constant potential density, and thus identify the paths of free movement by lateral mixing or flow. Sigma-*t* values have the advantage over salinity of increasing continuously with depth, and thus a certain ambiguity is avoided in identifying the layer from which a sample is collected.

OXYGEN-DENSITY CORRELATION OF SARGASSO SEA WATER

To define the oxygen-sigma-*t* correlation of the Sargasso Sea, 2,759 samples from

*Contribution No. 688 from the Woods Hole Oceanographic Institution.
†Part of this research was sponsored by the Office of Naval Research under Contracts Nonr 27701 and 769 (00).
‡ICHIYE (1954) has recently employed oxygen-chlorinity correlations to distinguish the types of water present in the seas adjacent to Japan and to recognise the sources of the waters which result from their admixture.

175 hydrographic stations occupied in the area between 30 and 40°N. latitude, west of 40°W. longitude, and east of the " Gulf Stream " were considered. In order, to eliminate water of Gulf Stream or other origin, all samples from stations showing salinities less than 36‰ at depths less than 500 metres were excluded.

The correlation between the oxygen content and sigma-*t* of these samples from the Sargasso Sea is shown in Fig. 1. The oxygen content gradually increases with

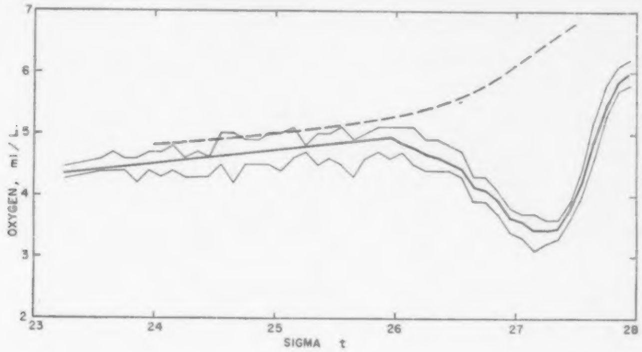


Fig. 1.

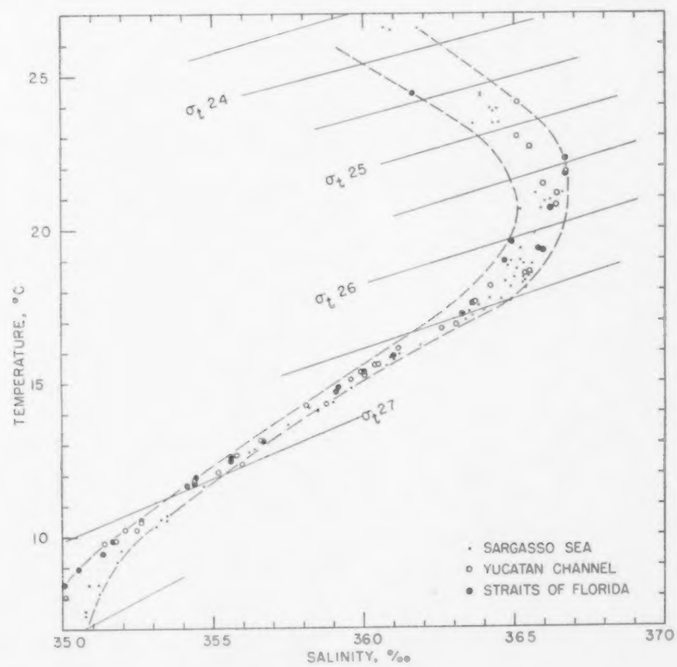


Fig. 2.

density until sigma-*t* values of 26·0 are reached, and then decreases rather rapidly until minimum values are encountered at about 27·3, in good agreement with SEIWELL'S (1937) finding that the statistical value of sigma-*t* at the oxygen minimum is 27·23 in the western basin of the North Atlantic. At greater densities, the oxygen

content increases to concentrations of about 6·0 ml./litre at sigma-t values slightly less than 28·00. In this range, below the oxygen minimum, there is rather wide scatter in the values, owing at least in part to the steepness of the curve.

Between σ_t = 23·5 and 25·95, the correlation is the linear least squares regression, in which the standard error of estimate is $\pm$ 0·29 ml./litre. The layer in which these densities are found is thin and shallow, and the number of observations in water having these densities is small, ranging from 10 to 70 samples in each 0·1 sigma-t unit span. In the denser waters, the correlation is the arithmetic average of all observations made within 0·1 sigma-t unit ranges. The envelope shown on Fig. 1 contains half of all the observations.

The dashed line in Fig. 1 shows the concentration of oxygen in fully saturated waters having the salinity-temperature characteristics of Sargasso Sea water (see Fig. 2). The linear part of the oxygen-sigma-t correlation (between σ_t = 23·5 and 25·95) is practically parallel to the saturation curve, but everywhere falls somewhat below saturation. In the denser layers, typical Sargasso water is well under-saturated.

OXYGEN SIGMA-t CORRELATIONS AND ANOMALIES

The correlations between oxygen and sigma-t have been examined in sections across the Yucatan Channel from Cuba to the Yucatan Peninsula, across the Florida Straits

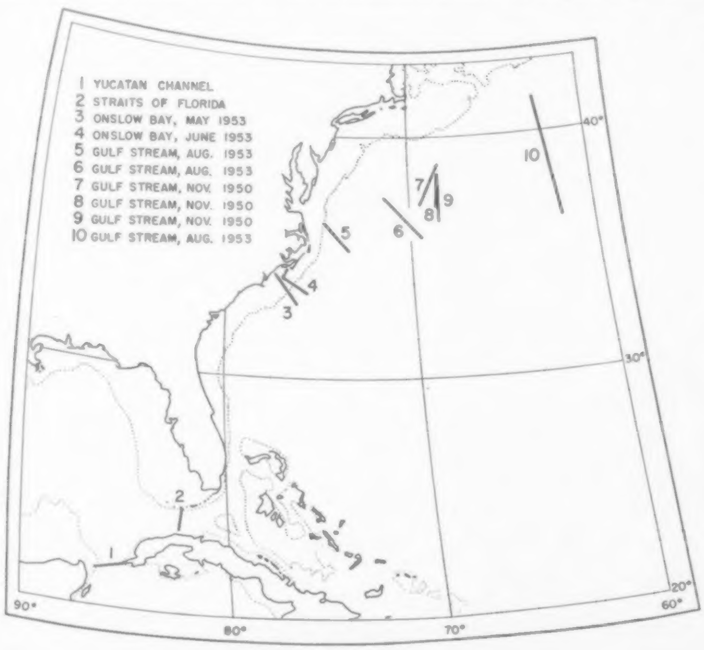


Fig. 3.

from Key West to Havana, seaward from Onslow Bay, North Carolina, and in six sections across the Gulf Stream between Cape Hatteras and Nova Scotia (Figs. 3 and 4). It is evident from Fig. 4 that these sections contain waters with considerably less oxygen than Sargasso Sea water of the same sigma-t. In treating the data, oxygen anomalies were estimated by subtracting the oxygen content of Sargasso water of

Table I

Sections showing the distribution of negative oxygen anomalies of more than — 0·50 ML/L.

No.	*Section*	*Station numbers*	*Dates*	*Positions at ends*	*Range of depths (metres)*	*Largest anomaly observed. (ml./l.)*	*References*
1	Yucatan Channel	1604- 1610	4 V '33- 5 V '33	21°36′N. 86°26′W 21°51′N. 85°00′W	60-620	— 1·41	SEIWELL, 1938 RAKESTRAW, *et al.*, 1937 Bull. Hydro., 1934
2	Straits of Florida	2003- 2007	4 III '34- 4 III '34	23°15′N. 82°16′W 24°18′N. 82°11′W	55-610	— 2·12	SEIWELL, 1938 Bull. Hydro., 1935
3	Onslow Bay, May	C-172- C-182	12 V '53- 14 V '53	33°01′N. 76°06′W 34°27′N. 77°27·5′W	54-444	— 1·63	—
4	Onslow Bay, June	C-183- C-192	8 VI '53- 10 VI '53	33°25′N. 75°41′W 34°31′N. 76°44′W	100-700	— 1·73	—
8	Gulf Stream	4842- 4853	20 X '50- 22 X '50	37°03′N. 68°29′W 38°36′N. 68°22′W	40-610	— 1·49	WORTHINGTON, 1954
9	Gulf Stream	4853- 4867	22 X '50- 26 X '50	38°36′N. 68°22′W 36°33′N. 68°33′W	50-600	— 1·46	WORTHINGTON, 1954
7	Gulf Stream	4868- 4882	30 X '50- 2 XI '50	38°56′N. 68°17′W 37°06′N. 69°19′W	60-650	— 1·22	WORTHINGTON, 1954
5	Gulf Stream	5084- 5094	10 VIII '53 12 VIII '53	36°20′N. 74°37′W 35°11′N. 73°19′W	38-365	— 1·43	—
6	Gulf Stream	5095- 5106	19 VIII '53 21 VIII '53	37°28′N. 71°12·W 35°50′N. 69°25′W	83-312	— 1·53	—
10	Gulf Stream	5107- 5122	26 VIII '53 29 VIII '53	36°25′N. 61°59′W 41°21′N. 62°48·W	90-580	— 0·83	—

All stations occupied by *Atlantis* except *Caryn* stations C–172 to C–192

the same sigma-t value, as obtained from the correlation curve shown in Fig. 1, from the observed oxygen content of the sample, and these anomalies have been plotted in the diagrams of the sections (Table I and Figs. 5-14).

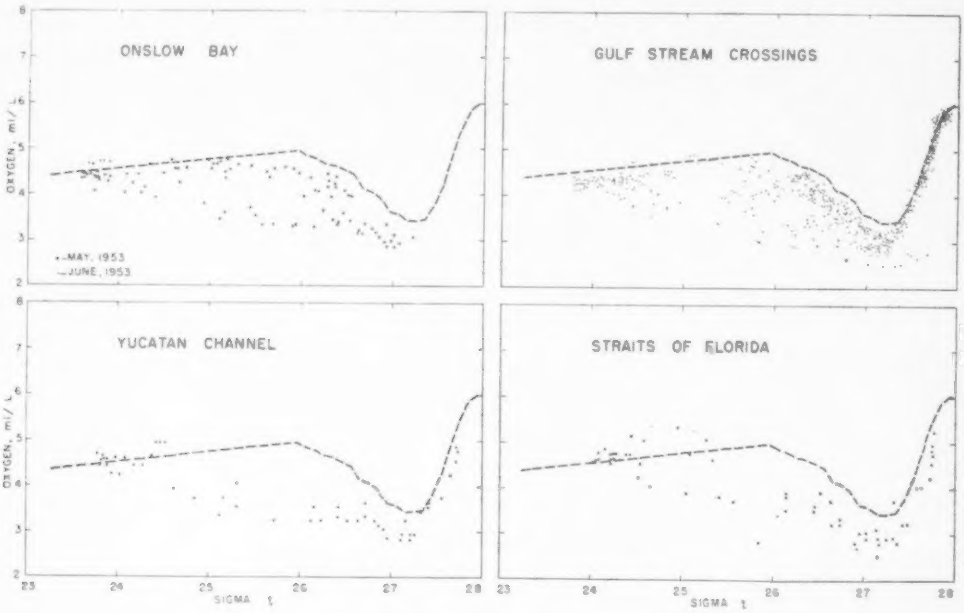


Fig. 4.

In order to eliminate slope water and waters of coastal origin, a diagram showing the salinity-temperature correlation of all samples from the Yucatan Channel and Florida Straits sections, and from the most southerly stations in the six Gulf Stream crossings, was prepared (Fig. 2)*. Samples which were significantly less saline, for the correlated temperature, than the left hand envelope shown in Fig. 2 were excluded as being of neither Caribbean nor Sargasso Sea origin.

Anomalies smaller than $\pm$ 0·5 ml./litre have not been considered significant.

YUCATAN CHANNEL AND STRAITS OF FLORIDA—SECTIONS 1 AND 2

Negative anomalies of at least 0·5 ml./litre were present in quantity in the upper 600 metres of these sections (Figs. 5 and 6). The most deficient water lay between sigma-t values of about 25·00 and 26·50, where anomalies up to $-$ 1·41 ml./litre occur in the Yucatan Channel and $-$ 2·12 ml./litre in the Straits of Florida.

Anomalies of more than $-$ 0·5 ml./litre were found in both sections in a separate zone below the 27·50 sigma-t surface. These are related to the extremely low oxygen minima noted by ROSSBY (1936, p. 37), who pointed out that these low oxygen concentrations, unlike those of the upper layers, cannot be traced through the Florida Straits.

*This salinity-temperature correlation represents waters slightly fresher, at any temperature, than ISELIN's (1936) correlation for Central Atlantic water between Chesapeake Bay and Bermuda.

ONSLOW BAY, MAY AND JUNE, 1953—SECTIONS 3 AND 4

In May (Fig. 7), negative anomalies were limited to the upper 500 metres, but they extended to greater depths in June (Fig. 8). It appears that the Florida Current was hugging the shore more closely in June than May. This is shown by the more inshore location of the 26·50 isopycnal, which was also steeper and correspondingly deeper in June.

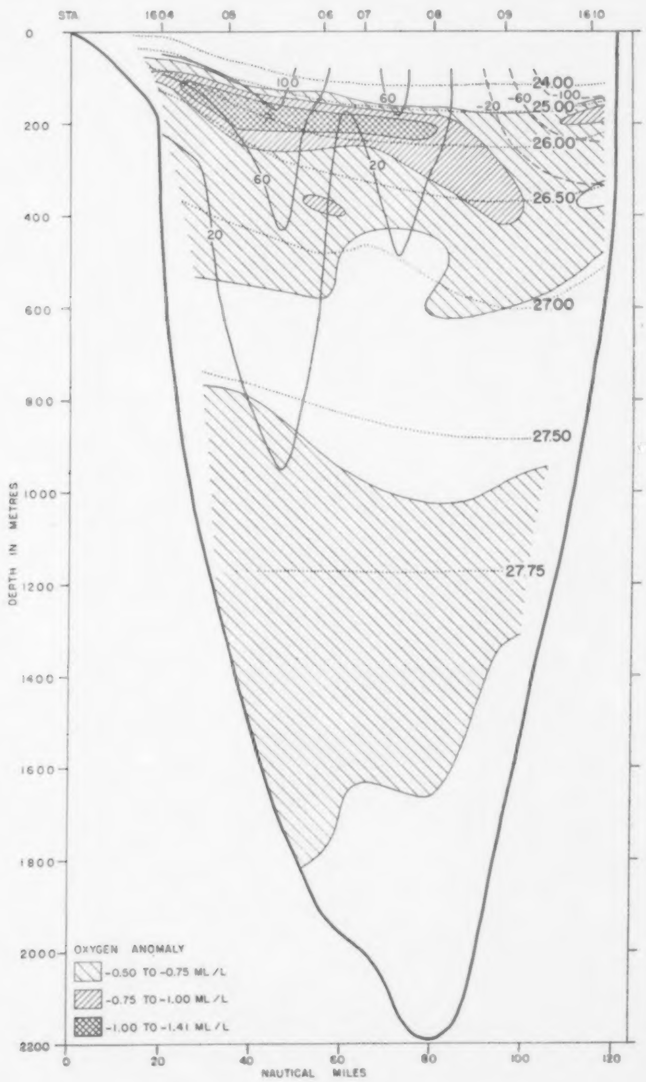


Fig. 5.

The oxygen anomalies were centered around $\sigma_t = 26{\cdot}00$ in May, but in June, most of them were in denser waters, and they appeared in two discrete portions;

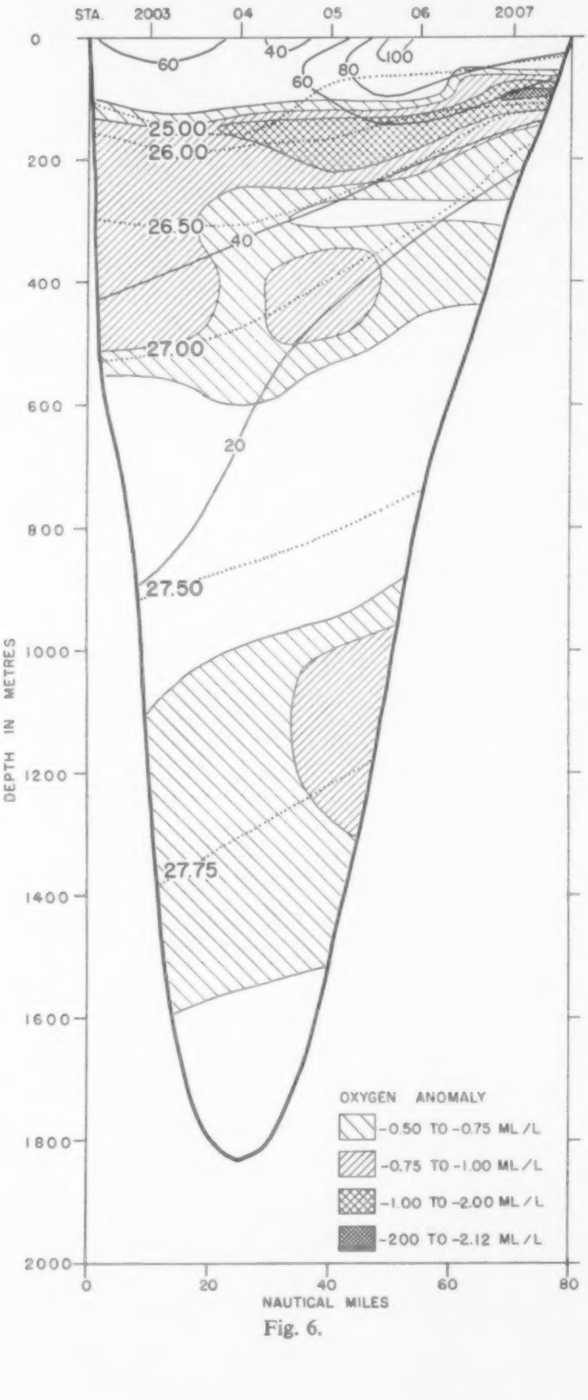

STA. 2003 04 05 06 2007
60
40
100
80
60
25.00
26.00
26.50
40
27.00
20
27.50
27.75
DEPTH IN METRES
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0 20 40 60 80
NAUTICAL MILES
OXYGEN ANOMALY
-0.50 TO -0.75 ML/L
-0.75 TO -1.00 ML/L
-1.00 TO -2.00 ML/L
-2.00 TO -2.12 ML/L

Fig. 6.

the main body was close inshore, but a separate portion was observed between 100 and 200 metres at Stations 183 and 184, suggesting a filamentous dichotomy in waters of Caribbean (or other southerly) origin at these latitudes. This discontinuous distribution of the oxygen anomaly will be shown in other sections.

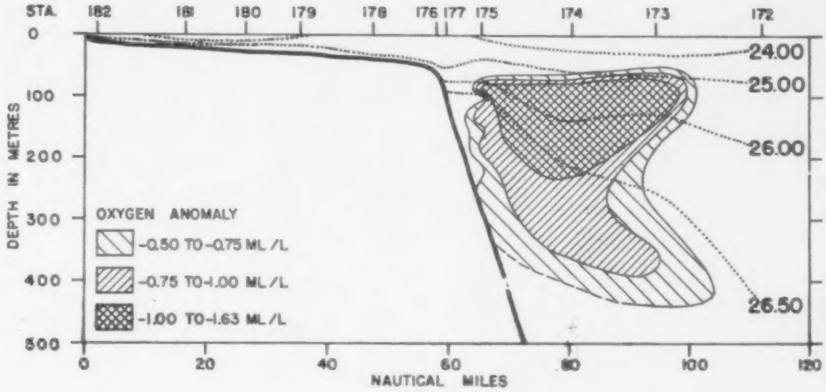


Fig. 7.

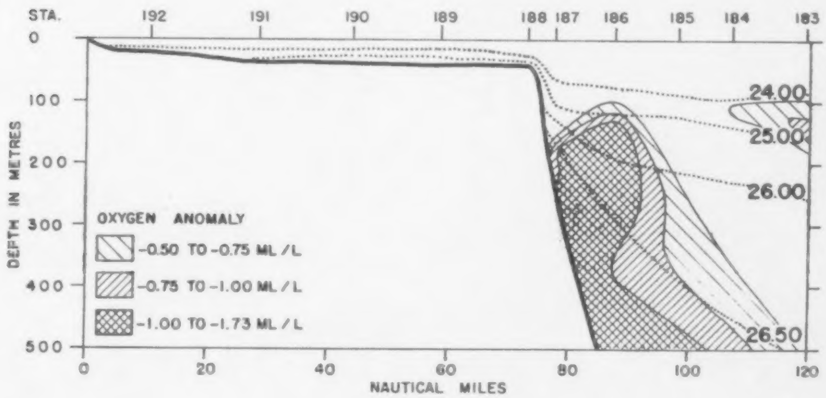


Fig. 8.

THE GULF STREAM—SECTIONS 5 THROUGH 10

Three sections across the Gulf Stream were occupied in October and November, 1950 (Figs. 9, 10 and 11). In all three, anomalies of at least − 0·5 ml./litre were found extending between something less than 100 to about 600 metres. The greatest deficiencies were centred at sigma-*t* values of about 26·00. In many cases the lines of equal anomaly can and have been drawn approximately parallel to isopycnals in order to suggest isentropic mixing with adjacent water masses of equal density.

Three additional sections across the Gulf Stream were occupied in August, 1953 in an attempt to make observations of oxygen anomalies along the course of the stream as nearly synoptically as possible from one ship. These sections (Figs. 12, 13 and 14) show remarkable contrasts with the sections occupied in 1950. Water anomalously low in oxygen was present in much smaller amounts, and was shallower in 1953 than in 1950. With one exception it was confined to the upper 300 metres

in 1953, compared with 600 metres in the previous sections. The highest anomalies were found at sigma-t values between 25 and 26 in Sections 5 and 6, and at about 26·5 in Section 10 as well as in the 1950 sections. The maximum anomalies in Sections 5 and 6 were about the same as in the 1950 sections (— 1·43 and — 1·53 ml./litre in 1953 compared with — 1·49, — 1·46, and — 1·22 in 1950) but in Section 10, the maximum anomaly was only — 0·83 ml./litre.

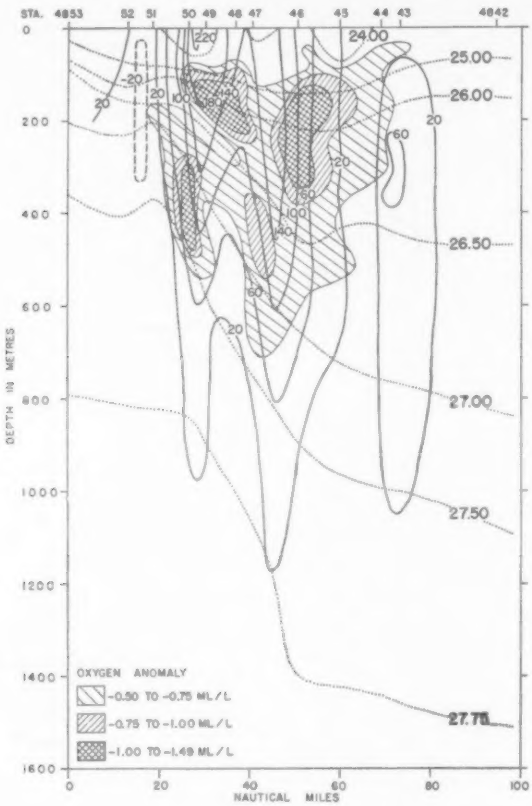


Fig. 9.

OBSERVATIONS EAST OF 61°W LONGITUDE

Water which meets both the oxygen and salinity anomaly criteria for Caribbean water has been observed by *Atlantis* in at least three stations (Table II) east of the area covered by Gulf Stream Section 10. These data are too scanty to draw any conclusions regarding the distribution of Caribbean water in this region, but Station 4811, occupied at 41°23′N. and 43°23′W., shows that Caribbean water can be identified in this region by the oxygen-sigma-t relationship.

RELATIONS BETWEEN OXYGEN ANOMALIES AND CURRENTS IN THE GULF STREAM SYSTEM

In all three of the Gulf Stream sections occupied in 1950 (Nos. 7, 8 and 9, Figs. 9

10 and 11) the largest anomalies were found below the maximum current velocities* This suggests that the swiftest moving water retains its characteristic anomaly for the greatest distance, except in the surface layers, where reoxygenation by vertical turbulence would be expected to be most rapid. The highest anomalies are displaced slightly to the south (right) of the maximum velocities suggesting that isentropic mixing is most effective along the north side of the current (to the left, facing down-

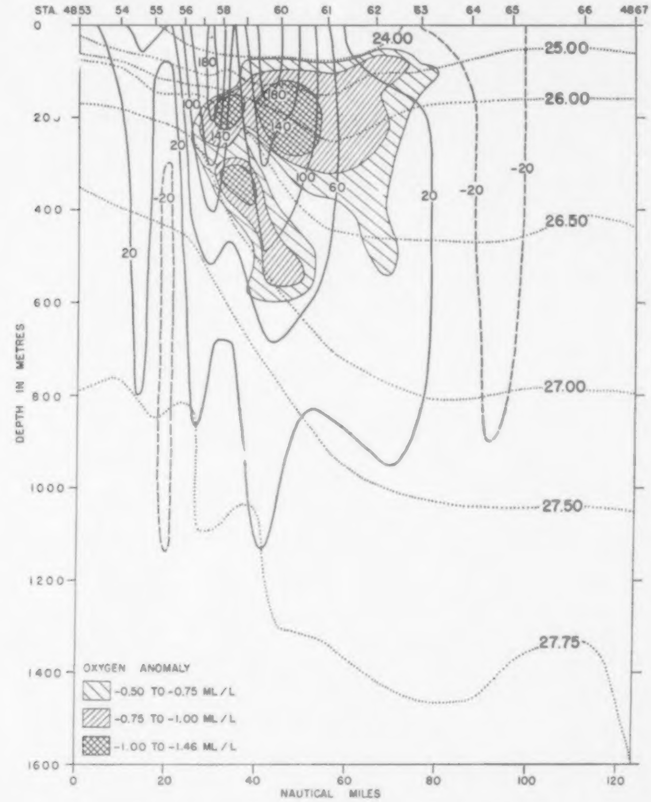


Fig. 10.

stream). Below the surface layers, the time factor appears to have had the least effect in mixing and reoxygenation of the swiftest waters. This last effect is particularly evident in Section 6, Fig. 13, occupied in August, 1953. The small mass of anomalous water is found below the highest velocity observed in any of the six sections between Cape Hatteras and Nova Scotia, and contains the most highly anomalous (— 1·52 ml./litre) water observed in the region.

The envelope of — 0·5 ml./litre anomalies is continuous but deeply lobed and otherwise irregular in Gulf Stream Sections 5, 7, 8 and 9 and is broken into three discrete portions in Section 6 and into four in Section 10. WORTHINGTON (1954) commented on the irregularities in the velocity profiles of Section 7, 8 and 9 and

*The velocity structure and other physical characteristics of these sections, and the hydrographic methods used have been described by WORTHINGTON (1954).

pointed out that these irregularities did not appear in the corresponding G.E.K. current measurements at the surface and at 100 metres. The irregularities and discontinuities which appear in the oxygen anomaly profiles are evidently related to corresponding irregularities in the velocity profiles. This appears to substantiate

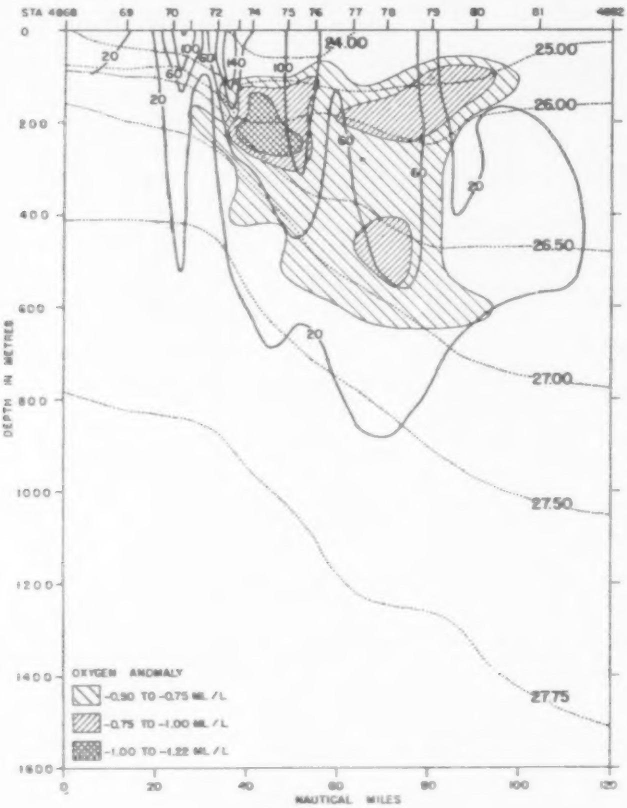


Fig. 11.

the velocity structures obtained by dynamic computations and perhaps to emphasize the tendency of G.E.K. observations to smooth and integrate velocity gradients.

Anomalies were found in counter-currents in all three of the 1953 sections (5, 6 and 10), and appear to extend continuously from the east-setting current to the counter-current. Between Stations 5112 and 5115 in Section 6*. It is tempting to associate this with an eddy or loop, but the observations are inadequate to test the possibility. The thin stratum of low oxygen water lying along the 26·50 sigma-*t* surface between

*The geostrophic velocity profiles of these 1953 sections were computed by the methods Worthington (1954) used, assuming a level of no motion at 2,000 metres. Attempts to make the crossings at right angles to the main course of the stream were based on bathythermograph observations of the so-called inshore front, which is marked by abrupt and distinct temperature changes. Section 6 contains the highest velocities yet found from dynamic computations in the Gulf Stream. These high velocities were confirmed by drift on station and set while underway as observed by frequent Loran fixes and dead reckoning.

Stations 5116 and 5122 is associated with the steepest thermal gradient at the 200 metre surface.

Section 6 is of some special interest, since it appears to demonstrate a rapidly moving jet-like structure, in which the main moving mass has retained its original characteristics, but in which the peripheral water has mixed so completely as to

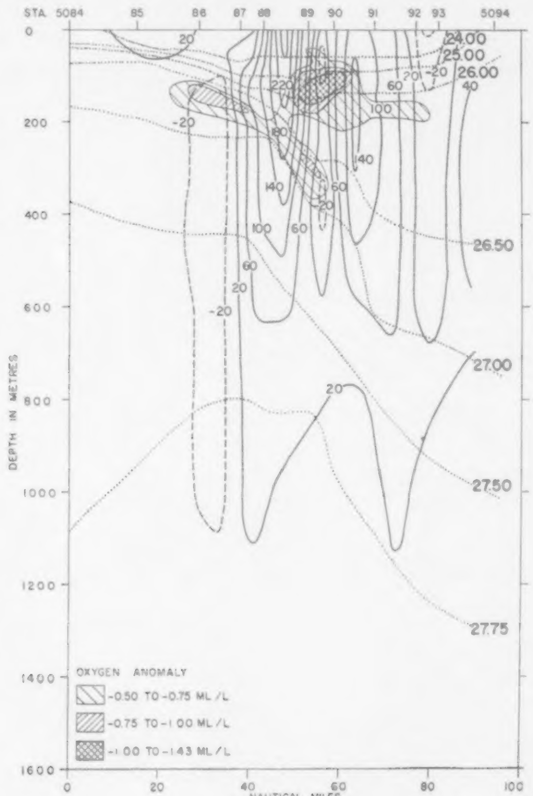


Fig. 12.

be no longer recognizable by its oxygen content. On the other hand, Section 10 represents a condition further downstream in which the currents are slower and more diffuse, and the oxygen anomalies have been maintained, although they are less intense than in the upstream sections, the waters being partially reoxygenated.

RELATION OF ANOMALIES TO TRANSPORTS

The transport of water, recognizable as of Caribbean origin by its oxygen content, across the sections can be computed by multiplying the planimetered area of the water having anomalies greater than — 0·5 ml./litre. *Oxygen deficits* can be estimated by multiplying these transports by the average anomalies. Deficits thus computed represent the difference in the oxygen content of the Caribbean water passing through a section in a unit of time and that of an equal volume of Sargasso Sea water. Thus,

the deficits are related to the transport, and are expressed in litres of oxygen per second. The computed transports and deficits of the sections are shown in Table III.

There is more than a four-fold variation in the transports, and nearly a five-fold variation in the oxygen deficits in the sections between Cape Hatteras and Delaware Bay (Sections 5 through 9). These amounts bracket the transports and deficits com-

Table II

Additional Atlantis stations where both salinity and oxygen anomalies indicate the presence of Caribbean water.

Sta. No.	*Position*	*Date occupied*	*Depth*	*Oxygen anomaly ml./l.*	*Salinity anomaly*
1047	37° 16′N.	19 VIII '31	87 m	− 1·37	*
	57° 54′W.		173	− 0·32	*
4762	38° 54′N.	13 VII '49	91	− 0·47	*
	60° 35′W.		135	− 1·02	*
			179	− 1·94	*
			261	− 1·00	− 4
			416	− 0·67	− 7
4811	41° 23′N.	19 VIII '49	97	− 1·07	*
	43° 23′W.		194	− 0·36	− 7

* Salinity-temperature falls within envelope on Fig. 2.

Table III

Transport of Caribbean water (anomalies of at least — ·5 ml./l.) and oxygen deficits in the section.

Section	*No.*	*Transport (10^6 m³/sec.)*		*Oxygen Deficit (10^6 litres/sec.)*	
		Current	*Counter-current*	*Current*	*Counter-current*
Yucatan Channel	1	1·72	0·41	1·32	0·32
Straits of Florida	2	2·09	—	1·79	—
Gulf Stream	7	2·83	—	2·13	—
,, ,,	8	2·46	—	2·20	—
,, ,,	9	2·69	—	2·31	—
,, ,,	5	0·67	0·02	0·47	0·01
,, ,,	6	0·83	0·002	0·90	0·001
,, ,,	10	0·58	0·17	0·39	0·11

puted for the Yucatan Channel and Straits of Florida sections. It is known that the transport through the Straits of Florida varies widely at different times. Montgomery (1941) computed the transport in four sections off Havana and found that it varied between 26·0 and 30·3 × 10^6 cubic metres per second, and Wertheim (1954), computing the transport from the electric potential between Key West and Havana, found that it varied between 14 and 39 × 10^6 cubic metres per second during the period between August, 1952 and July, 1953. The total mass transport in the Straits of Florida Section (No. 2) was computed by Montgomery to be 26·0 cubic metres per second, which is very close to the average mass transport estimated by Wertheim

(27×10^6 m^3/sec). Proportionately, the transport of Caribbean water (with anomalies greater than $-$ 0·5 mlO_2/litre) could be expected to vary between 1·08 and 3·02 million cubic metres per second and the oxygen deficit to vary between 0·92 and 2·58 million litres per second. The ranges of these quantities observed in Sections 5 through 9 are quite close to the above ranges, but the degree to which the waters have been reoxygenated by mixing cannot be estimated without better information on the distribution of oxygen and velocity across the Straits of Florida at the times corresponding to the departure of these waters from that region.

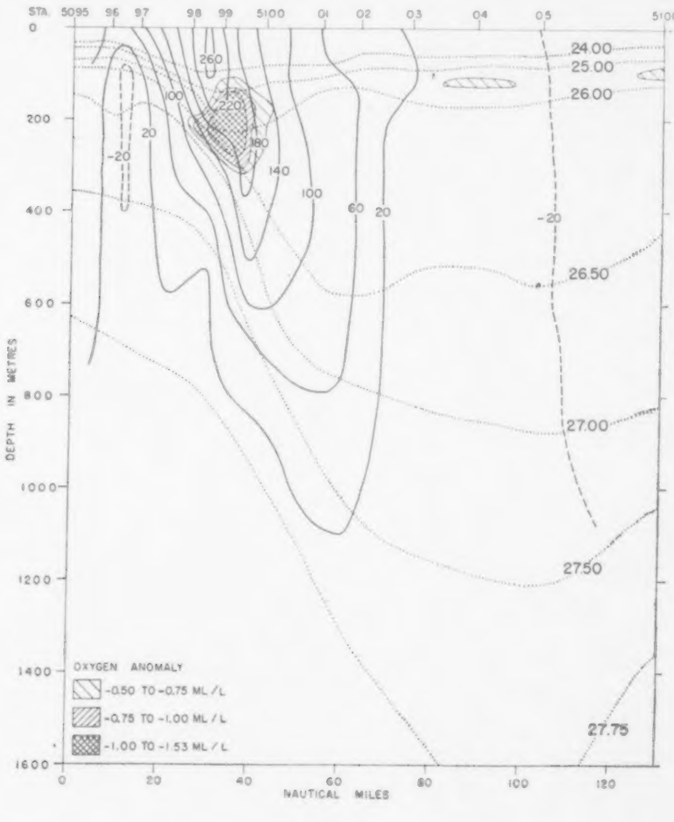
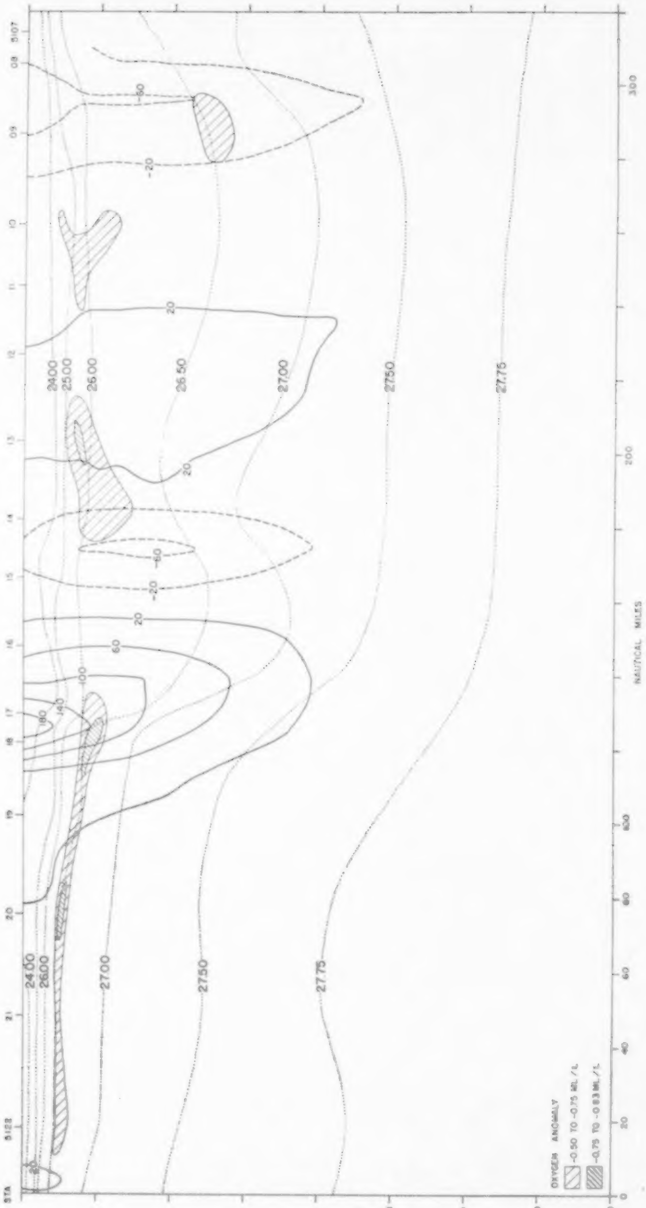


Fig. 13.

ISELIN (1940) computed that the mass transport of the Gulf Stream between Montauk Point and Bermuda varied between 93 and 76×10^6 cubic metres per second in 13 sections occupied between June, 1937, and January, 1940. It is apparent that the transports we have computed are smaller than ISELIN's, but ours are limited to water which is clearly marked as of Caribbean origin by its oxygen content, and the velocity structures show that more water than this is in motion relative to the 2,000 metre level.

A further point of interest lies in comparison of Sections 5 and 6, in which both the transports and the anomalies are larger in the downstream section (No. 6)



STA
DEPTH IN METRES
NAUTICAL MILES
OXYGEN ANOMALY
-0.50 TO -0.75 ML/L
-0.75 TO -0.83 ML/L

Fig. 14.

suggesting that a large decrease took place in the transport through the Straits of Florida, between the times of the emergence of these two water masses.

DISCUSSION

Negative oxygen anomalies are characteristic of the Caribbean, where they are present in quantity as shown by *Atlantis* observation of 1933 and 1934 (Parr, 1937 ; Rakestraw and Smith, 1937 ; Seiwell, 1938, Bulletin Hydrographique, 1934, 1935). The possibility that there are substantial increments of water of this type to the Gulf Stream *via* the Antilles Current has not been eliminated, and sufficient data are not now at hand to examine this possibility fully. Seiwell's section C (Seiwell, 1934) from Bermuda to Hispaniola is not in sufficient detail, particularly in the upper 200 metres, to answer this question; examination of other stations occupied by *Atlantis* in the Bermuda-Hispaniola-Bimini Triangle indicate that waters meeting the oxygen and salinity criteria for Caribbean water are present, but in quite small amounts.

The Straits of Florida section may give the order of magnitude of the amounts of oxygen-low water which are available from the Caribbean to the Gulf Stream. It would have to be assumed that only a portion of the oxygen deficit emerging from the Straits of Florida will still exist at any point downstream, because of reoxygenation by vertical and isentropic mixing. According to Riley's (1951) estimates, it can be safely assumed that neither photosynthesis nor respiration will appreciably change the oxygen concentrations in this water mass during the time it remains unmixed in the area between Florida and Nova Scotia. Riley estimated that consumption of oxygen in the Atlantic proceeds at the average rate of 0·21 ml./litre/year at the sigma-t 26·5 surface, and that the rate decreases to 0·15 ml./litre/year at the sigma-t 26·9 surface. Thus, except for aeration from the surface, the oxygen content should be conservative throughout the area, and it should be possible to estimate vertical and isentropic mixing coefficients from the downstream decrease of oxygen anomalies. However, this is made difficult by fluctuations in the increments of water of southern origins to the Gulf Stream system.

It is probable that variations in the flow of the Florida Current out of the Straits of Florida can account for the wide variations in the transports and oxygen deficits observed north of Cape Hatteras. If there are increments of this oxygen-low water *via* the Antilles Current, variations in this contribution might augment or dampen the effects of variation in the Florida Current. The causes of these latter variations are beyond the scope of this paper, but they may include (a) periodic fluctuations associated with the tides in the North Atlantic Ocean, the Gulf of Mexico, and possibly the Caribbean Sea (von Arx, Bumpus and Richardson, 1954), (b) non-periodic fluctuations related to the Atlantic wind system (*op. cit.*, Wertheim, 1953 ; Chase, 1954 ; Stommel, private communication), and (c) seasonal variations. The discontinuous observations of the oxygen anomaly at hand are insufficient to establish correlations with any of these factors. However, Wertheim and von Arx *et al.*, have established that there are major fluctuations in the structure and transport of the Florida Current off Havana and off the North Carolina coast; in the latter locality it has been shown that these can occur within very short time intervals (hours). Iselin (1940) observed that there was a seasonal periodicity in the fluctuations in the

transport of the Gulf Stream between Montauk Point and Bermuda between June, 1937 and January, 1940.

The discontinuous distribution of oxygen anomalies appears to afford some confirmation of FUGLISTER'S (1951) multiple current Gulf Stream theory. FUGLISTER pointed out that this multiple stream system extends at least as far southwest as Cape Hatteras. The distribution of the oxygen anomalies in the June, 1953, Onslow Bay section, as well as VON ARX and RICHARDSON'S (1953) airborne observations of a discontinuous feature in the surface temperatures of the Florida Current and the Gulf Stream, suggest that the multiple current system may exist and have its genesis south of Hatteras. The discontinuous distribution of oxygen anomalies in Gulf Stream Sections 5 and 6, and their appearance in the counter-currents in Sections 4, 5 and 6, show that these waters are materially related to waters of southern origin and that the several currents and counter-currents observed contain southern water, not merely momentum transferred from southern sources.

CONCLUSIONS

1. The oxygen-sigma-*t* correlation provides a means of identifying water of southern origins in the Gulf Stream and of delineating the Stream's right-hand boundary. The relationship is especially useful in the temperature range 10 to 18 °C, where Florida Current-Caribbean Sea waters cannot easily be distinguished from Sargasso Sea waters by temperature and salinity.

2. The oxygen-sigma-*t* correlation in the Caribbean Sea, the Yucatan Channel, and the Straits of Florida shows that the Caribbean is the primary source of Gulf Stream water, although the possiblity that there are increments from the Antilles Current has not been eliminated.

3. Oxygen anomalies in two sections seaward from Onslow Bay support other observations that there are significant fluctuations and discontinuities in the Florida Current south of Cape Hatteras.

4. Wide variations in the amount of Caribbean water detectable in the Gulf Stream by the oxygen anomaly are observed between Cape Hatteras and Nova Scotia, confirming the occurrence of major fluctuations in the mass transport of the Gulf Stream.

5. Discontinuities in the oxygen anomaly in Gulf Stream sections downstream from Cape Hatteras tend to confirm FUGLISTER'S multiple stream theory.

6. The presence of water marked by oxygen anomalies in the separate filaments of the current and in the counter-currents of the Gulf Stream shows that these currents are materially related and do not represent merely the transfer of momentum from southern sources.

ACKNOWLEDGMENT

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A non-metallic water sampler*

THOMAS G. THOMPSON and TSAIHWA J. CHOW

(*Received January* 1955)

Summary—A syringe type water sampler made of Lucite is designed for collecting sea water at any depth without the sample becoming contaminated by contact with the metal. The sampler has been used with success in the investigation of trace metallic ions in the ocean.

INTRODUCTION

IN STUDYING the distribution of trace metallic ions in sea water at various depths, ordinary water sampling bottles (SVERDRUP *et al.*, 1942; FJARLIE, 1953) which are made of metals or alloys, cannot be used as exposure of the water sample to metal produces contamination. This contamination may cause errors of several thousand fold. The authors have found that any sampling device made of metals or alloys which has been coated, plated or painted with protective substances (WÜST, 1932) is unreliable for taking samples for trace metal analysis. Water samplers designed primarily for biological studies (ZOBELL, 1941; JENSEN and STEEMAN-NIELSEN, 1953) are composed of evacuated glass bottles which are opened by messengers at the desired depths. Such bottles either will not withstand great hydrostatic pressure or will limit the size of the sample. JENSEN and STEEMAN-NIELSEN stated that their sampler is limited to a depth of 125 metres. The ZOBELL bottle limits the size of the sample. To eliminate the various objections, a non-metallic water sampler for chemical investigation has been designed to secure uncontaminated samples of sufficient volume at any given depth.

DESCRIPTION OF THE WATER SAMPLER

A line drawing of the water sampler is shown in Fig. 1. In Fig. 2 are photographs of the apparatus; the picture at the left shows the position for securing a sample and that at the right portrays the position after the sample has been taken. The photograph in Fig. 3 shows the detail of the tripping mechanism.

The water sampler is constructed primarily of Lucite, but the tripping mechanism is of stainless steel. The apparatus is constructed to operate on the principle of a syringe and is so designed that the water sample is never in contact with metal. The main part of the water sampler consists of a cylindrical Lucite chamber, *L*, which has a capacity of 1,750 ml. The chamber is about 36 cm high and has an outside diameter of 10·2 cm. The wall of the chamber has a thickness of 0·64 cm. The top of the chamber consists of a split keeper, *I*, and cylinder top, *J*, made of Lucite (Fig. 1) which are held in position by stainless steel screws embedded in the Lucite, the heads of which are covered with plastic cement. Atop the split keeper and

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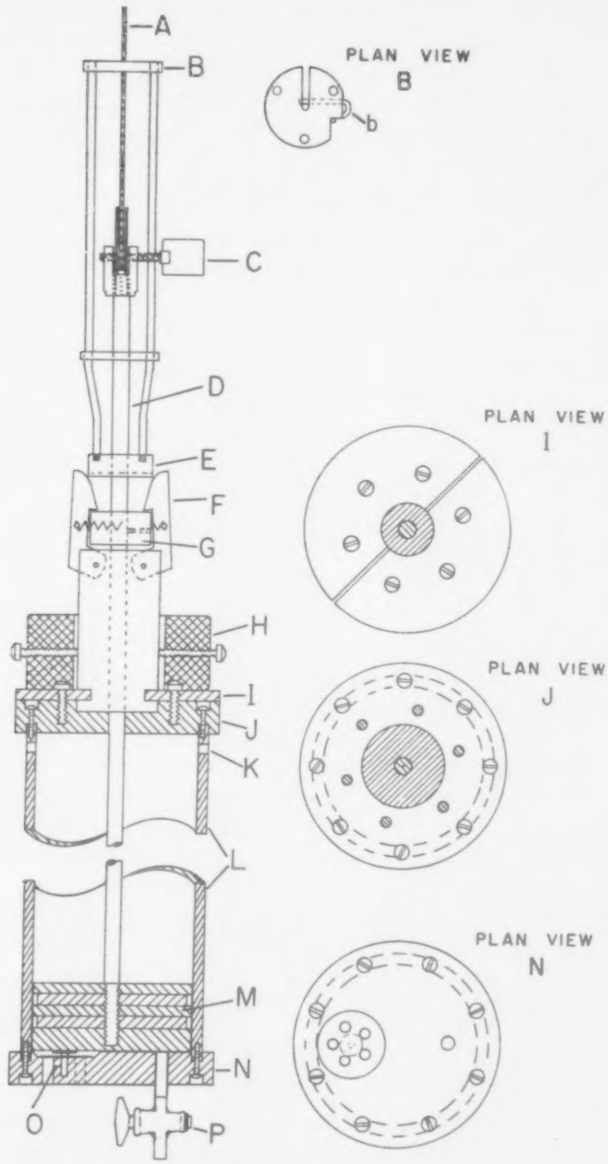

Fig. 1. A schematic drawing of the water sampler.

Legend

A Cable
B Tripping Cage
b Safety Pin
C Screw Cable Clamp
D Piston Rod
E Moveable Tripping Collar
F Hooks of Tripping Mechanism
G Fixed Collar
H Lead Weight
I Split Keeper
J Cylinder Top
K Vent Holes
L Lucite Chamber
M Piston
N Cylinder Bottom
O Intake Valve
P Stopcock

attached to the movable chamber is a lead weight, *H*, of about 5 kg which causes the Lucite chamber to drop when the tripping mechanism is released. A hole in the centre of the cylinder top and the lead weight permit the sliding of the piston rod, *D*. The piston, *M*, is attached to the lower end of the piston rod and is composed of three Lucite discs and two Lucite rings which have been machined so as to fit tightly against the wall of the chamber, *L*. The cylinder bottom, *N*, is also made of Lucite and is attached in the same manner as the cylinder top. The intake valve, *O*, for drawing a water sample into the main chamber, consists of five holes drilled into the cylinder bottom. Over these holes is a flutter valve of gum rubber or plastic held in place by a Lucite screw. A stopcock, *P*, is inserted into the cylinder bottom and permits the removal of the water sample.

In operation, the water sampler is attached to the cable, *A*, the clew of the cable is connected to the top of the piston rod with a screw clamp, *C*. A movable safety pin, *b*, holds the cable in position in the tripping cage, *B*. In the cocked or sampling position, the piston rests snugly on the bottom of the main chamber, *L*, and the hooks, *F*, of the tripping mechanism are firmly latched over the fixed collar, *G*, thus supporting the weight of the water sampler. As the apparatus is lowered into the sea, water will flow through the vent holes, *K*, filling the air spaces above the piston. When the water sampler has been lowered to the desired depth, a messenger, sliding down along the cable strikes the top of the tripping cage, *B*, thereby causing the tripping collar, *E*, to unlatch the supporting hooks, *F*. When the apparatus is tripped, the lead weight, *H*, causes the main chamber to slide downward around the piston, *M*. As the Lucite chamber drops, the piston remains stationary. The water in the chamber above the piston is forced out through the vent holes at the top of the chamber as the water sample is being drawn into the chamberat the desired depth through the intake valve, *O*. The distance between the vent holes and the intake valve is such that the water being sampled is unaffected by the discharge of the slightly less dense water. The actual process of sampling, after the tripping mechanism has been released, requires from 30 to 60 seconds. When the apparatus has been hauled aboard ship, the water sample is removed through the stopcock, *P*. The removal of the water sample is facilitated, when the stopcock, is opened, by slowly raising the chamber to the cocked position; the piston thus forces the water from the chamber into the receptacle in which the sample is to be stored.

DISCUSSION

The water sampler has been used with success at sea on numerous occasions. Its advantages may be summarized as follows: Water samples of ample volume can be collected at any depth without the sample becoming contaminated; the apparatus is of relatively simple construction, can be operated with ease, is comprised of durable material and is fairly inexpensive to construct.

In practice the water sampler has two shortcomings: (1) insufficient weight to allow rapid lowering to the desired depth, and (2) no provision for collecting samples from several depths during one lowering. Because of these shortcomings, considerable time is required for the collection of samples from several depths at a given station. These shortcomings can be remedied, however, by addition of sufficient

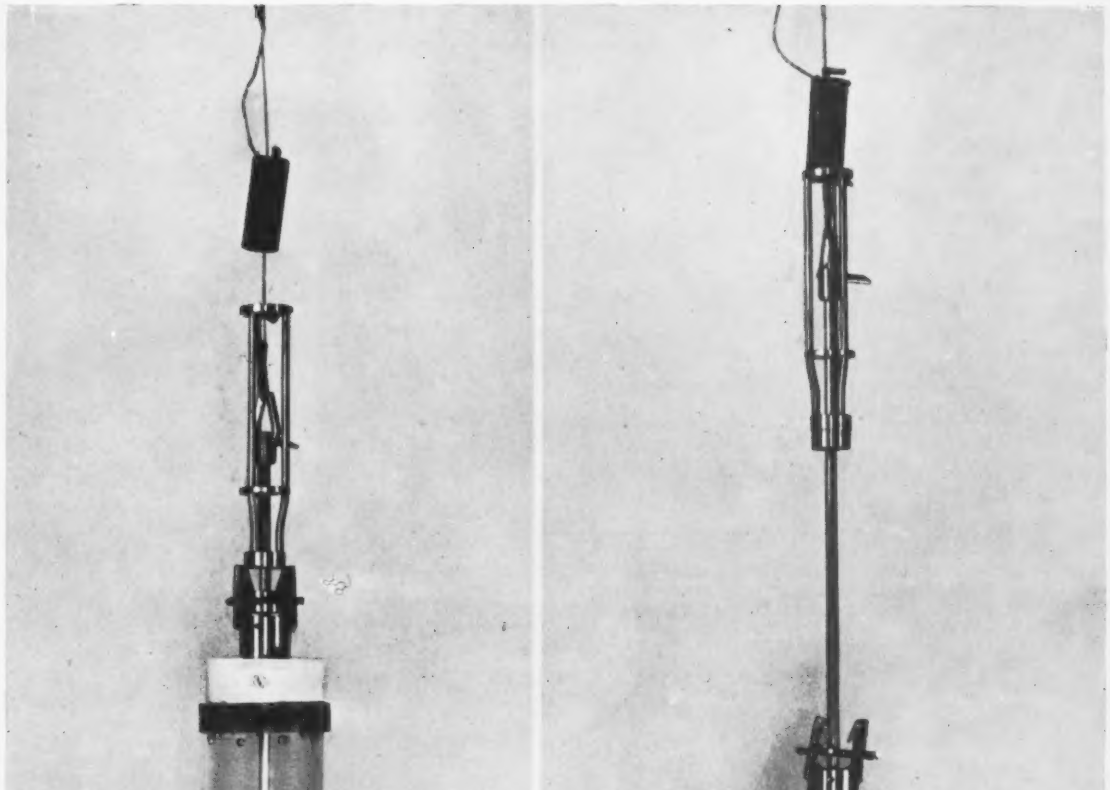

Fig. 2. Photographs of water sampler. Picture at left shows bottle in the cocked or sampling position; that at the right shows the position after sampling.

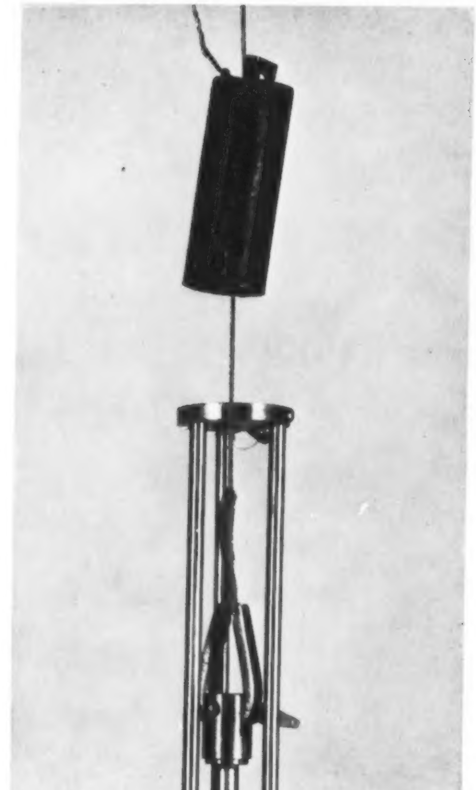

Fig. 3. The tripping mechanism of the water sampler.

weight to permit rapid lowering and by appropriate modifications in design to allow collection of samples from several depths during one lowering.

Department of Oceanography, University of Washington, Seattle, Washington.

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The electrical effects of tidal streams in Cook Strait, New Zealand

B. H. Olsson

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Summary—Electric currents which are generated by tidal streams have been observed in the land near the coast of Cook Strait, New Zealand. In each tidal period, the vector representing the horizontal component of the potential gradient was found to rotate through 360° in a counter-clockwise direction. Corresponding rotary streams were observed in the Strait.

The potential gradient associated with those streams which are directed along the channel is explained by the theory worked out by Longuet-Higgins (1949). No theory is available for dealing with on-shore streams.

Using the potential-gradient measurements, the magnitudes of those streams directed along the channel were computed. These computed values agree with certain direct observations of the streams made by the survey vessel H.M.N.Z.S. *Lachlan*.

1. INTRODUCTION

In 1946, on the shores of the English Channel, Longuet-Higgins (1949) measured earth potentials which were caused by tidal streams. He derived a theory connecting the horizontal potential gradient and the streams, showing that earth currents were induced by the movement of the sea water relative to the vertical component of the earth's magnetic field.

In 1949, some measurements were made near Wellington, New Zealand. It was hoped that the principle might later be used to observe the very changeable streams of Cook Strait.

The measurements extended over a little more than a lunar month, from 30 August to 3 October, 1949. Preliminary tests with a number of electrode spacings showed that the gradient was reasonably uniform over the area. Two pairs of electrodes were connected to recording millivoltmeters to give the components of the potential gradient in approximately north-south and east-west directions. From these records the average tidal and solar-diurnal cycles of the gradient were extracted. In what follows, they are compared with some recordings of tidal streams.

2. RECORDING INSTALLATION

The site of the recording installation is shown in Fig. 1. The district is rugged, with grass-covered hills up to 1,700ft. high dissected by deep valleys. Along the coast, sea-cut cliffs rise steeply for several hundred feet.

Non-polarising, copper : copper-sulphate electrodes, with the electrolyte in porous pots, were buried about one foot deep in positions where the ground was permanently damp. The north-south electrodes were placed about one kilometre apart in the valley of the Karori Stream. The east-west electrodes were placed about one kilometre and a half apart, at Tongue Point and at the recording site near the mouth of the Karori Stream. The distances between the electrodes, which were all about 50 feet above sea level, were measured on aerial photographs of the area.

Field-telephone cables, which were laid on the ground around the cliffs, connected

the electrodes to the recording hut. The two recorders were clockwork-driven and had a sensitivity of about 400 millivolts full-scale, with about 6,250 ohms circuit resistance. Every minute, each recorder printed on its chart a dot whose position corresponded to the potential difference between the associated pair of electrodes. Every fourth minute, the electrodes were disconnected from the recorders and zero-potential marks were printed.

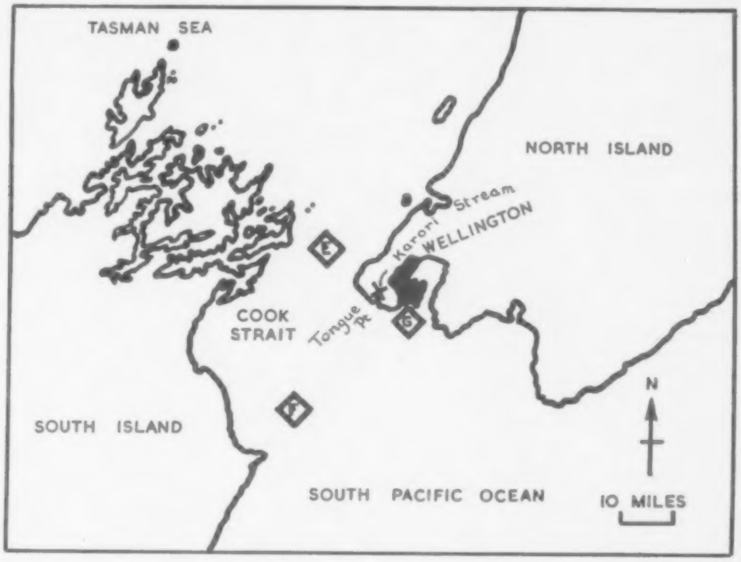

Fig. 1 upper.

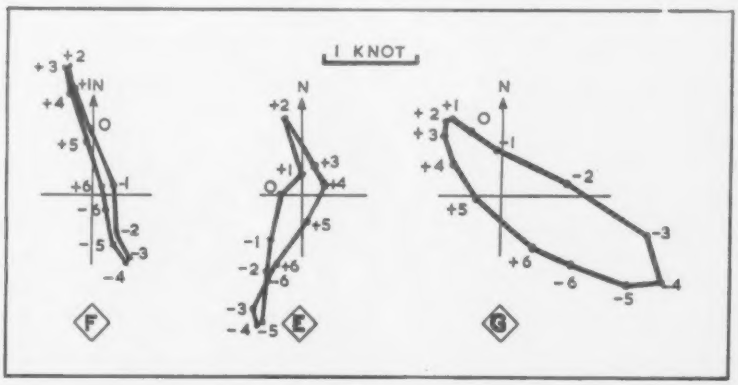

Fig. 1 lower.

Fig. 1. Cook Strait, New Zealand, with stream observations. The site of the earth-potential observations is marked by a cross. The tidal streams were observed by H.M.N.Z.S.*Lachlan* at *E* on 15 May, 1951, at *F* on 18-19 May, 1951, and at *G* on 23-24 July, 1951. In the vector diagrams, a line drawn from the origin to any point on the diagram represents the vector stream at the indicated number of hours before or after high water at Wellington.

3. ANALYSIS OF RECORDS

A typical day's records are shown in Fig. 2. New Zealand Standard Time, which is twelve hours ahead of Greenwich Mean Time, is marked on the records.

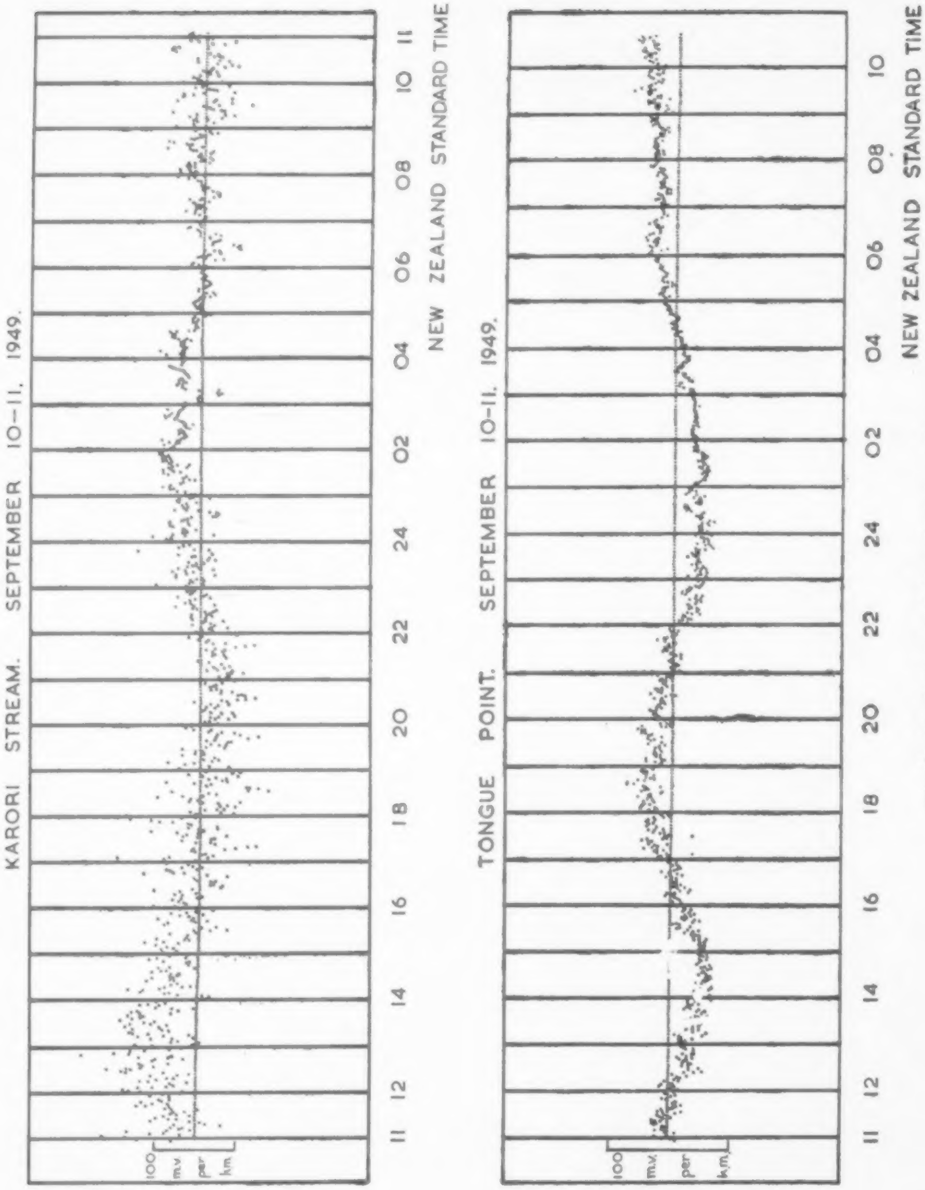

Fig. 2. Typical potential-gradient records.

The points on the records show considerable scatter. It has been found that some of this is caused by magnetic storms, but the large scatter in daylight hours is attributed

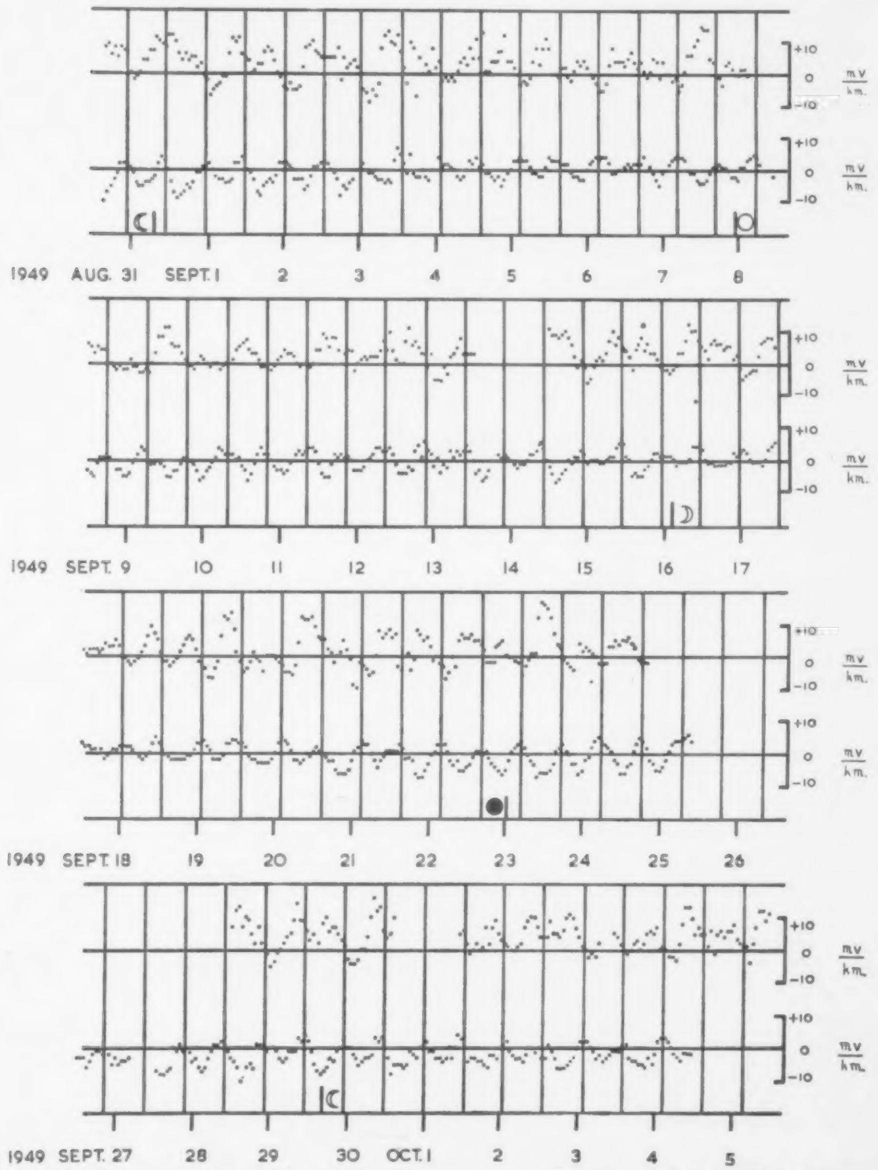

Fig. 3. Hourly means of potential gradient. The upper rows of means are from the Karori Stream observations with the positive gradient to the north. The lower rows of means are from the Tongue Point observations with the positive gradient to the west. The vertical lines through the sets of means show the times of high water at Wellington.

to electric trams in Wellington city, about five miles from the site of the observations. As the tramway system operates on direct current there is, in addition to the transients produced as the trams start and stop, a continuous leakage current which depends

at any time on the number of trams in use. This leakage current may be expected to cause potential gradients which vary slowly during most of the day. Thus the solar-diurnal variation computed from the records has a doubtful meaning.

3·1 *The Solar Diurnal Variation.*

The whole series of recordings is summarised in Fig. 3. Each point represents the mean potential gradient during an hour, the means being made visually from the original records. The gaps in the sequence in Fig. 3 are due to cables breaking or to other mishaps.

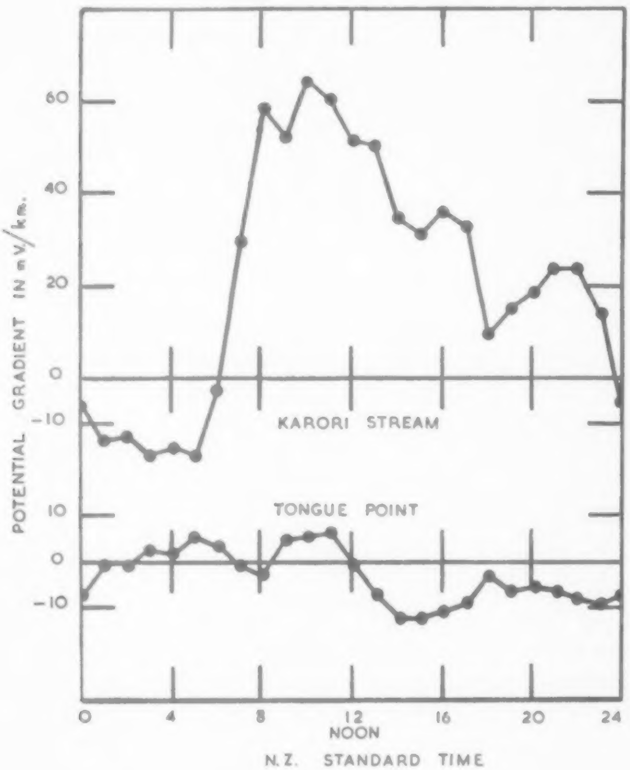

Fig. 4.

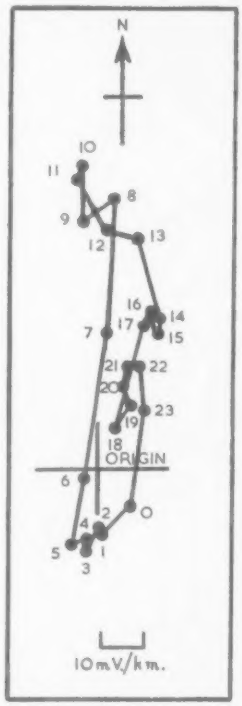

Fig. 5.

Fig. 4.—Fig. 5. Mean solar-diurnal variation. In Fig. 5, a line drawn from the origin to any point on the diagram represents the vector potential gradient at the indicated number of hours after local midnight.

The vertical lines on Fig. 3 mark the times of high water at Wellington as predicted in the New Zealand Nautical Almanac (1949). It is evident on inspection that the recordings have a major oscillation whose period is tidal. To eliminate this, and to obtain the solar-diurnal cycle, averages were taken over 29 days for each hour of the solar day. The average daily cycles are shown in Fig. 4 and they have been combined into a vector plot in Fig. 5.

The solar variation, which has an amplitude greater than would be expected from

the flow of water in the Strait, appears mainly on the Karori Stream records. As these records also show the greater scatter from the tram transients, it is probable that much of the apparent solar-diurnal variation is due to tramway leakage currents.

Thus it appears that little information relating to the tidal streams can be obtained from these diagrams.

3·2 *The Tidal Variation.*

To estimate this component, it was thought desirable to make new averages of the original records. The hourly intervals were made to start afresh at each predicted time of high water at Wellington. As the sequence of values was very similar to Fig. 3 it is unnecessary to show it. Means over the 29 days were found from this sequence for each hour after high water. The resulting tidal cycles are shown in Fig. 6 and they are combined into a vector plot in Fig. 7.

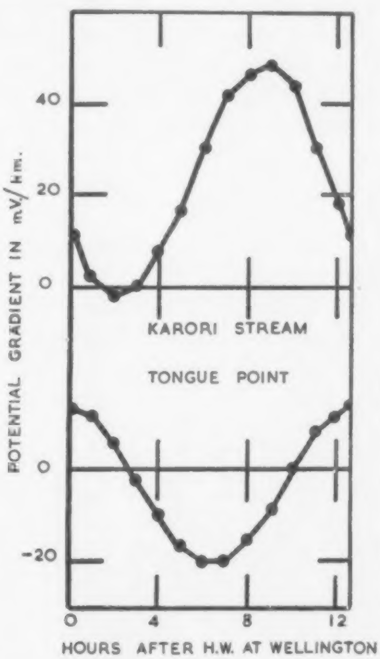

Fig. 6.

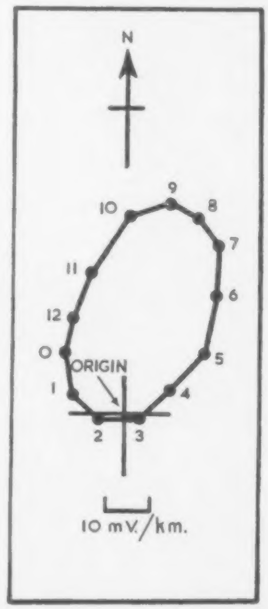

Fig. 7.

Fig. 6—Fig. 7. Mean tidal variation. In Fig. 7, a line drawn from the origin to any point on the curve represents the vector potential gradient at the indicated number of hours after high water at Wellington.

It would have been more correct to have used the time of lunar transit rather than the time of high water, but the difference between these two varies by not more than $1\frac{1}{2}$ hours so that the effect on the plots of Figs. 6 and 7 is presumably small.

Longuet-Higgins (1949) has examined the electric potential gradient that is caused by a flow of sea water along a uniform channel. The gradient in the land is at right angles to the channel. Cook Strait is too irregular in shape for this theory to apply without reservations, but it seems reasonable in this set of observations to

compare the streams parallel to the coast with the electric potential gradient at right angles to it. The direction at right angles to the coast is approximately the line joining the points marked 2 and 8 in Fig. 7. The variation of gradient in this direction is almost the same as that shown for the Karori Stream in Fig. 6.

In the next section we attempt to deduce what streams parallel to the shore would account for the gradient and we later compare them with some stream observations.

An overall drift of water through the Strait may explain the predominance of positive values of the gradient at Karori Stream, but this comparison will not be pursued because electrode measurements at this site are probably biassed by leakages of direct current from the tramways.

4. AMPLITUDE OF TIDAL STREAMS, USING POTENTIAL-GRADIENT DATA

The notation used in this section is that of Longuet-Higgins (1949). In discussing the English Channel he assumes, as a reasonable approximation to actual conditions, that a channel has a semi-elliptical cross-section and is of infinite length. A stream of fluid whose conductivity is κ_1 flows in this channel with a velocity V (supposed uniform over the cross-section). The channel lies in a semi-infinite bed of material of uniform conductivity κ_0. If the strength of the vertical component of the earth's magnetic field is H_y, the potential gradient $\partial\phi/\partial x$ across the stream is given by

$$\frac{\partial\phi}{\partial x} = \frac{V H_y \tanh \xi_1}{(\kappa_0/\kappa_1) + \tanh \xi_1}$$

where $\tanh \xi_1$ is the ratio of the minor (vertical) to the major (horizontal) axis of the ellipse.

Sections taken through Cook Strait vary considerably over a few miles. However, as an approximate value, $\tanh \xi_1$ may be taken as 2×10^{-2} (channel = 11 nautical miles wide, 110 fathoms deep). The basement under Cook Strait is greywacke (with some tertiary mudstone overlying this in places). For greywacke

$$\kappa_0 = 5 \times 10^{-5} \text{ (ohm–cm)}^{-1}.$$

By measurement, κ_1 has been found to be 0·04 (ohm–cm)$^{-1}$. Therefore

$$\frac{\kappa_0}{\kappa_1} = 1{\cdot}25 \times 10^{-3}.$$

Also, H_y for Wellington = 0·535 gauss. By substituting these values, and changing to practical units, it is found that

$$\frac{\partial\phi}{\partial x} = 26 \text{ mV/km/knot}.$$

This is the uniform potential gradient in the channel. Longuet-Higgins has shown that the potential ϕ in the plane of the channel bed, at any point outside the channel can be written

$$\phi \propto e^{-\xi} \cos \eta$$

where ξ and η are the elliptic coordinates of the point. On the surface, where $\cos \eta = 1$

$$\phi \propto e^{-\xi}.$$

By differentiating this with respect to x (the distance on the surface from the centre

of the channel, at right angles to the channel), and by changing to rectangular coordinates, it is seen that

$$\frac{\partial\phi}{\partial x} \propto \left[\left(\frac{x}{k}\right)^2 - 1\right]^{-\frac{1}{2}} \exp\left(-\cosh^{-1}\frac{x}{k}\right).$$

For a channel whose width is much greater than its depth, $2k$ is approximately equal to the width of the semi-ellipse representing the channel.

The exponential portion of this equation represents the variation in the potential gradient on the surface outside the channel. At the site of the potential gradient observations

$$\frac{x}{k} = 1{\cdot}36.$$

The above equation shows that the gradient measured will be 0·47 times the gradient in the channel, that is

12·3 mV/km/knot.

These calculations are based on the assumption that the stream flows in a long uniform channel. For Cook Strait, this assumption is not entirely valid.

Except near the turn in the Strait, however, the theory should apply to streams flowing along the channel. The values of the constants in the equations for the potential gradient are such that any likely variation in the ellipses chosen to represent the channel will make little difference to the computed potential gradient.

The theory will not apply to cross-channel streams or to any streams near the turn in the Strait.

From Fig. 7, the potential gradient which is equivalent to a stream along the channel can be found. It has a maximum amplitude of about $\pm$ 25 mV/km for the tidal component. The calculations show that the corresponding tidal stream will have a maximum rate of $\pm$ 2 knots. This is the average maximum rate for the lunar month.

As the variation of the stream rate with depth is not known for Cook Strait, the stream rate on the surface cannot be found from the mean values calculated from the potential-gradient observations. Probably the surface stream rates will be a little higher than those calculated.

5. COMPARISON OF TIDAL STREAMS AND POTENTIAL-GRADIENT OBSERVATIONS

Unfortunately, very few quantitative data relating to the streams in Cook Strait are available. The water flow is apparently very complex, and much affected by meteorological conditions, while the rough seas that are often encountered make observations difficult.

Some comments on the tidal streams in Cook Strait are given in "The New Zealand Pilot," (1946) but the comments there are of too general a nature for detailed comparison with the potential-gradient observations to be possible.

Nearly two years after the potential gradients were measured, some continuous observations of the streams were made by H.M.N.Z.S. *Lachlan* during a hydrographic survey. Observations were made on one day at each of four stations, three of which are marked on Fig. 1. Tables of tidal-stream velocities prepared from these observations now appear on the charts of Cook Strait (1951) and Wellington Harbour

(1950), but we shall consider here only the actual observations. These have been made available by the Hydrographic Section of the New Zealand Navy Department, and are shown as vector plots in Fig. 1.

The point G is nearest to the electrode sites. Its plot in Fig. 1 shows some overall drift of water to the east, but the variable part of the stream has its highest values at 1 or 2 hours after high water at Wellington and at 4 hours before it. The stream is then directed along the coast. These times agree well with the times of maximum electric gradient in Fig. 7. The senses of the stream and gradient agree with the theory ; that is, the gradient is to the left hand of the direction of the water flow. This is the opposite law to that described by LONGUET-HIGGINS, but the direction of the vertical component of the earth's magnetic field is reversed in New Zealand when compared with its direction in England. The maximum streams observed at point G were about $\pm 1\frac{1}{2}$ knots. This is not very different from the ± 2 knots deduced in the last section.

The streams in Cook Strait vary with the weather, so it is not surprising that the cycle of stream flow on a single day at point G should be less sinusoidal than the cycle of potential gradient averaged from a month's records.

Lastly, we need to consider the potential gradient along the coast. It is greatest about $1\frac{1}{2}$ hours before and 5 hours after high water at Wellington. Presumably it is caused by water flow. At its time of maximum, the tidal components of the streams at points E and F (see Fig. 1) are small and cannot be the cause. There is, however, a stream at point G directed more or less at right angles to the coast, and streams setting on-shore have been noticed near Tongue Point. Such streams may be the cause of the potential gradient parallel to the coast. There are other possible causes, but they will not be discussed here since the observations are too limited at present.

6. CONCLUSION

The tidal streams in Cook Strait are accompanied by electric potential gradients in the land and, so far as it has been possible to check, they agree with the theory described by LONGUET-HIGGINS (1949). It is worth noting that both the observed stream and the gradients rotate in the same counter-clockwise sense.

If the principle is to be used to study the variable streams in the Strait, it seems very desirable to have a theory to connect the streams with potential gradients in an irregular channel where the flow may be complicated.

7. ACKNOWLEDGMENTS

The author wishes to thank the Commanding Officer, H.M.N.Z.S. *Lachlan* and the New Zealand Naval Board for making available the original stream observations which were made in Cook Strait.

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Alternative analyses of current surveys*

F. C. FUGLISTER

(*Received 22nd January* 1955)

Summary—Ocean current nomenclature, with respect to average and instantaneous currents, is discussed. Temperature data from the Gulf Stream System, obtained in 1948, 1951 and 1953, and from the Kuroshio System in 1933 are analysed with alternative points of view. A 1954 survey of a portion of the Gulf Stream System substantiates the analyses which show relatively small scale structure in these current systems.

INTRODUCTION

IN 1951 this writer advanced an hypothesis of multiple currents in the Gulf Stream System. This large scale breakdown of the current system differed from the generally accepted pattern in that it showed a series of overlapping currents and relatively weak countercurrents rather than one continuous, branching current. A breakdown in this current system on a smaller scale was suggested by VON ARX and RICHARDSON (1953). They showed that the " surface outcrop " of the currents could be followed by a plane for distances of not more than about 300 kilometres. Their interpretation of the observations showed a series of currents similar to those suggested by the author but on a considerably smaller scale and with no evidence of counter currents.

It is evident that as more detailed observations of ocean currents are obtained many heretofore unknown structural characteristics will come to light, and the simple concept of a major ocean current " flowing like a river through the sea " may become a thing of the past. It will become increasingly important that the time and space scales employed in any study or description of these currents be clearly understood. An associated problem, of real importance in this connection, is one of nomenclature. By attaching a name to an observed current, many factors are implied – or assumed on the part of the reader – that are not correct or justified on the bases of the actual observations. Since this paper deals with currents, and it is difficult to avoid using names, a brief discussion of the subject of ocean current nomenclature is in order.

NOMENCLATURE

Most of our knowledge of ocean currents is based on data collected and averaged over many years. These data are of many different kinds but primarily they consist of ships' drift reports. The subsurface data are meagre in comparison and consist almost entirely of temperature and salinity observations ; direct sub-surface current measurements are negligible in number. The ocean current names in the literature, therefore, refer to long period average water movements at the surface and, what in effect is, a mixture of average and quasi-instantaneous water movements at depth.

Ocean currents are named in order to locate, at least approximately, the geographical positions of the currents and to differentiate one from another. Names are

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applied only to those currents that are considered to be relatively permanent features of the general circulation. Whether the name applies to an average or to an instantaneous current is not generally made clear. The same name, with the singular form of the word " current " or " stream," is used to denote either or both.

Confusion could be avoided if it was generally accepted that the major ocean currents named in the literature refer to large scale, long term average water movements and that the plural form of the word " current " should be used. A current observed at a particular place and time is best described not by a name but by an accurate statement as to its location, velocity, transport, water-mass characteristics, etc. It may be referred to as part of a larger scale average water movement but it should not be considered the same thing.

In particular, it is suggested that the term Gulf Stream should not be used in reference to a particular current observed at a particular time. The Gulf Stream is a large scale water movement in the central, western North Atlantic where, on the average, the flow is to the north and east. It is narrowest and swiftest in the area from the Straits of Florida to the offing of Cape Hatteras where it is close to the Continental Shelf. To the north and east of Cape Hatteras the average water movement is not close to the shelf and it is more wide spread, deeper and slower. To the east of about 45° west longitude it is even more diffuse and to the east of about 25° west longitude it is no longer recognizable as a particular average water movement. Individual surveys in these areas do not show any such current (Iselin and Fuglister 1948). This definition of the Gulf Stream differs from those given by Iselin (1936) and by Fuglister and Worthington (1951). Iselin confined the term Gulf Stream to that portion of the system flowing between Cape Hatteras and longitude 50° west. Fuglister and Worthington went a step further and restricted its application to a single continuous current in this same region. One purpose of the following analyses is to show that the Gulf Stream is a single continuous current only in a large scale statistical sense, and any particular current observed in this area is not the Gulf Stream and should not be confused with it by being given the same name.

TEMPERATURE DATA

Following the system used for other studies (Fuglister 1951, 1954) the assumption will be made here that major currents exist wherever there is an abrupt horizontal temperature gradient at a depth of 200 metres. The relationship that has been repeatedly observed between the temperature gradients at 200 metres and the slope of the sigma-t surfaces at greater depths is the justification for assuming that these temperature gradients are associated with more than just superficial currents. The direction of flow is such that, facing down stream, warm water is to the right and cool water to the left. This does not apply where the 200 metre temperatures are below 5° centigrade. At these lower temperatures the salinity differences are the determining factor and the direction of flow is generally in the opposite direction.

All of the surveys to be discussed cover periods of less than one month and the thermal conditions are presented without regard to time changes. The spacing of the observations vary but are generally less than 10 miles apart along the ships' tracks. In the case of the Pacific data the spacing of the observations is irregular, being close together near the coast but quite widely spaced in other areas. In all

cases except with the Japanese data, the temperature was obtained by means of the bathythermograph and the Fahrenheit scale is used**.

ALTERNATIVE ANALYSES

Alternative analyses of the temperature fields at a depth of 200 metres in various portions of the Gulf Stream System (Charts 1 to 3) and in the Kuroshio System (Chart 4) will be presented. In each case there is more than one interpretation of the data. Other interpretations are, of course, possible but not many that would be fundamentally different from these shown. Along the tracks of the vessels a linear interpolation between observations is adhered to, thus restricting the number of interpretations.

The method of surveying the temperature field differed in each of the surveys. In the first case (Chart 1) the Canadian Research Vessel H.M.C.S. *New Liskeard* crossed and recrossed the currents, changing course by 180° at the end of each run. In the second case (Chart 2) the *Albatross* III* made more widely spaced sections in a much longer survey. The third case (Chart 3) is quite different from the first two in that no attempt was being made to follow a current, and the temperature field is the result of combining data from two independent surveys. The Woods Hole Oceanographic Institution vessels *Atlantis* and *Caryn* were studying the western portion of the area while the H.M.C.S. *Sackville* was surveying the eastern sector. Finally, the Kuroshio investigation (Chart 4) was a Japanese, multi-ship survey of a very large area.

In each case presented here the temperature field obviously consists of a cool and warm water area separated by a zone in which abrupt thermal gradients occur. If the data had consisted of many hundreds of observations averaged over the years it is easy to visualize what the average thermal field would look like in each case. There would be one, relatively diffuse, gradient separating the cool and warm water areas. According to present terminology, this average gradient in the areas covered by Charts 1 and 3 would be termed the Gulf Stream ; in the area of Chart 2 it would be the northern branch of the North Atlantic Current. If this terminology is carried over and applied to these short period surveys there is a natural tendency to analyse the data in such a way as to produce a Gulf Stream or a branch of the North Atlantic Current. In other words, the isotherms are drawn so as to show one abrupt gradient crossing the charts.

Occasionally an analysis is forced in order to obtain a single gradient. An extreme example is shown here (Chart 3A) in order to point out the fact that it is always possible to twist and turn the isotherms in such a manner as to produce a single abrupt gradient. A less obvious example (Chart 2A) is the interpretation carried out aboard the *Albatross* III. The object of this survey was to locate and follow the northern branch of the North Atlantic Current and it is easy to see why the data were interpreted as shown here but it is entirely possible that, if the object of this cruise had been to survey a system of currents, the data might have been analysed as shown on Chart 2B. This latter analysis has, at least, the virtue of not suggesting that a current was following in the path of the ship.

** All the bathythermograph instruments were calibrated in the Fahrenheit system. The data were not converted to the metric system because the scale used is relatively unimportant in the analyses presented in this paper.

* Chartered by the Woods Hole Oceanographic Institution.

Another type of analysis shows a single current but manages to avoid violent and improbable meandering (Chart 1B, 1C and 3B). The " Gulf Stream " or single group of isotherms crosses the entire area ; the " extra " gradients are accounted for as eddies. The analysis carried out aboard the H.M.C.S. *New Liskeard* showed the " Gulf Stream " with an anticyclonic eddy to the north of it (Chart 1C) but these same data could be interpreted to show a current with a cyclonic eddy to the south of it (Chart 1B). A more complicated analysis of this type retains a " Gulf Stream " but several other currents and eddies are required to account for the " extra gradients (Chart 3B).

A third type of analysis, usually used only to cover very large areas, tends to show that, although numerous currents exist in an area, they all stem from a single current. The temperature field in the Kuroshio System for August, 1933, as drawn by Uda (1935), is an example of this point of view. Uda's chart was drawn with 3°C intervals ; the 1° intervals are interpolated here (Chart 4A) in order to compare this analysis with one carried out by the author (Chart 4B). The branching currents in the Kuroshio System, according to Uda, are shown on Chart 4C. A quite different picture of this system of currents (Chart 4D) is based on an interpretation of the 200 meter temperature field discussed below. Where several currents are shown stemming from a single one, it is generally necessary to introduce some eddies or countercurrents because the sum of the gradients that make up the branches is greater than the gradient in the single current.

Finally, there is an analysis that essentially dismisses the idea, introduced originally by the long period average picture, that there is necessarily a continuous single current passing through the zone that separates the cool and warm water areas. Although this type of analysis results in a much more complicated picture of the temperature fields and probable currents (Charts 1A, 2B, 3C, 4B and D) it may partially explain some of the peculiar behaviour of the " Gulf Stream " as pictured by the other types of analysis. The extreme meandering, the tendency for the current to follow the lines of observations, the downstream fluctuations in width, transport, velocity etc., all these questions take on new and different meanings with the introduction of these new " turbulent " pictures of the currents. Whether these interpretations are correct or not, they are clearly possible and should be given due consideration when studying the Gulf Stream or any other major ocean current system.

Two studies, that may throw more light on the validity of this last type of analysis, are first, a detailed examination over a period of days of one of the abrupt thermal gradients and second, a survey of the right hand or warm water environment of the Gulf Stream. Studies of the first kind are being made and the results of one such study will be discussed below. A thorough survey of the vast warm water environment of the currents in this area will require a great deal of ship time and in all probability will eventually require a multiple ship survey.

A DETAILED SURVEY OF A PORTION OF THE GULF STREAM

In August, 1954 a survey of a small portion of the Gulf Stream in the area south and east of Georges Bank and south of Nova Scotia was undertaken aboard the *Caryn*. From a position at approximately 35° north, 68° west the *Caryn* followed a current over a distance of 240 miles to a point near 29° north, 64°west. The dead reckoning – Loran – calculations gave speeds in this current of from 4 to 5 knots.

Near 39° north, 64° west (Chart 5) a short section was run across the thermal gradient associated with the current and a drift station was occupied. The current velocity, averaged over a period of 4 hours, was 3·7 knots, 053° true. Immediately after this section was completed another run was made, this time toward the north (section C on the chart). There was a marked change in the thermal structure which, taken together with the calculated drift, indicated a slowing down of the current speed and a bending to the north and northwest. The next section in point of time, section B, was essentially in the same geographical position as section A but 30 hours later. This section gave the same results as section A but the current had shifted 8 miles to the south during the time interval. At the end of section B the ship was again hove to and a drift station occupied.

On the bases of the data obtained up to this point it was to be expected that the ship would drift first toward the northeast and then gradually toward the north and west with diminishing speed. Actually, the drift started off toward the northeast but as the speed of drift diminished the direction changed, not toward the north, but east and then as the speed increased again, toward the south of east. The very light winds, less than Beaufort force two, and smooth seas together with excellent Loran conditions made it possible to get quite accurate and relatively small scale measurements of the surface current velocities during this drift. For each 2 hour period of this 14 hour drift station the velocities of the current were as follows ;

direction	070°	070°	070°	093°	098°	103°	120°
knots	4·5	3·9	3·6	3·1	3·9	3·8	3·8

After this drift station and a short excursion into the warm water area to the south, section D was occupied. Again the abrupt thermal gradients of the first two sections were crossed with even colder water in evidence. The diminishing gradients and changing conditions of section C were not encountered.

These sections are approximately 25 miles apart, which is considerably closer together than most sections made across these currents, yet if either of the last two sections were left out any interpretation of the data from this survey would be in error. If the last section was omitted it would be concluded that the current turned north in this area accounting for the warm water found to the north and west. On the other hand if the middle section, section C, was not available there would be no doubt that the current continued to the eastward and the warm water to the north would be considered to be part of a separate eddy. Certainly, all the data show that the abrupt thermal gradients, associated with these currents, can become diffuse or concentrated over a remarkably short, downstream, distance.

CONCLUSION

The data presented in this paper represent only a small part of the data examined during the past year. A collection of data, covering a period of five years, from the California Currents was examined at the Scripps Institution of Oceanography. It was while studying these data and the Kuroshio data that it first became apparent to the writer that a major difficulty in the way of understanding these currents is the tendency to force the quasi-instantaneous picture to conform with the statistical mean.

Relatively narrow and swift currents occur in the Gulf Stream System but our

present knowledge is not sufficient to tell us over what distances these currents remain narrow and swift. It is evident, however, that these characteristics of the currents can change over relatively short distances.

Theoretical conclusions concerning downstream changes in the physical characteristics of major ocean currents will frequently be erroneous as long as the present conglomoration of time and space scales is used to describe these currents.

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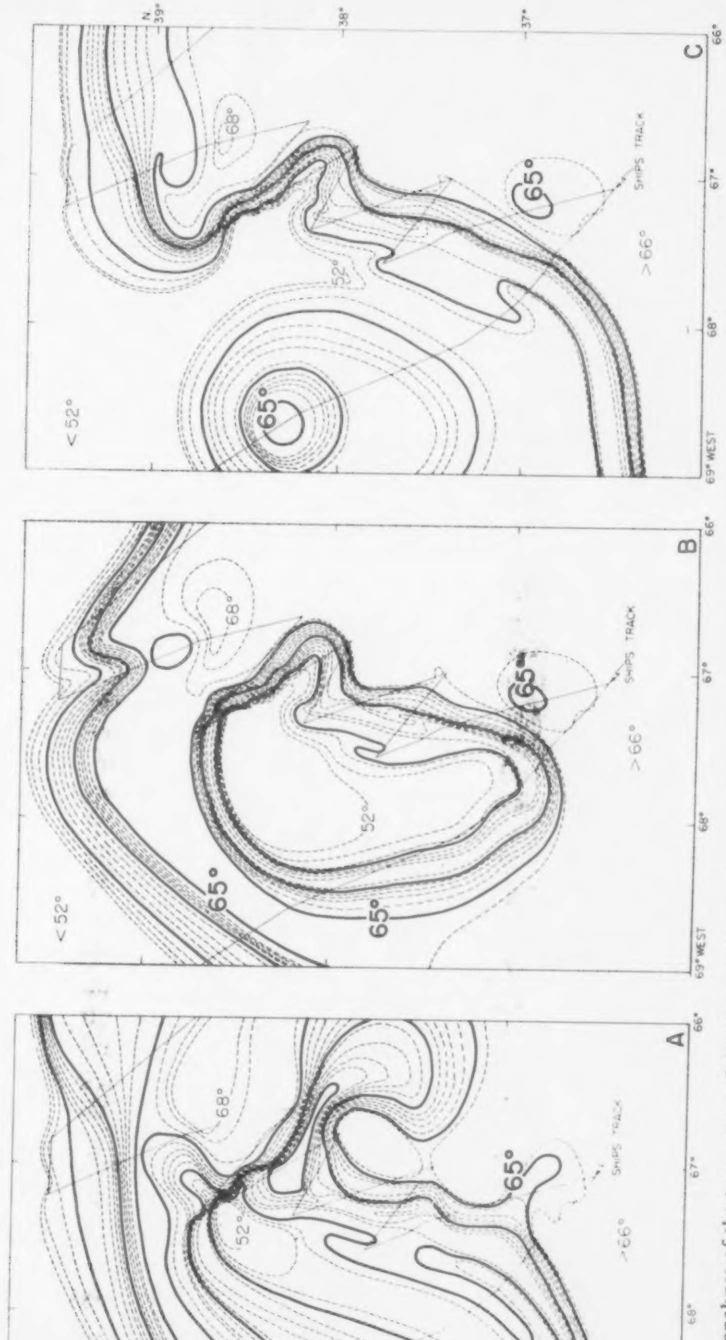


Chart 1. Three analyses of the temperature field (degrees F), at a depth of 200 metres in the Gulf Stream System south of Georges Bank. From data obtained by the Canadian Research Vessel H.M.C.S. *New Liskeard*, 15-18 November, 1948.

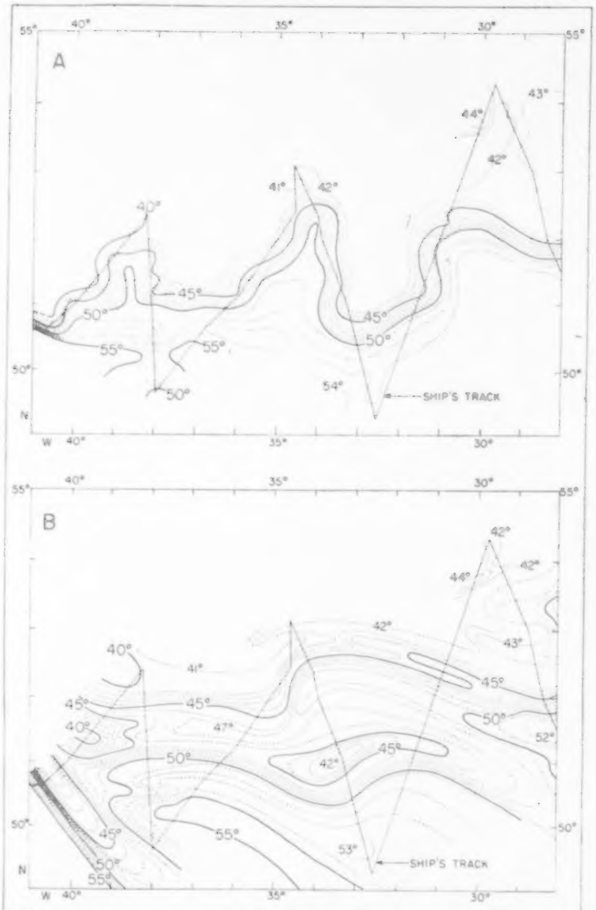


Chart 2. Two analyses of the temperature field (degrees F), at a depth of 200 metres in a portion of the Gulf Stream System in Mid-Atlantic. From data obtained by the Woods Hole Oceanographic Research Vessel *Albatross III*, 7-23 July, 1951.

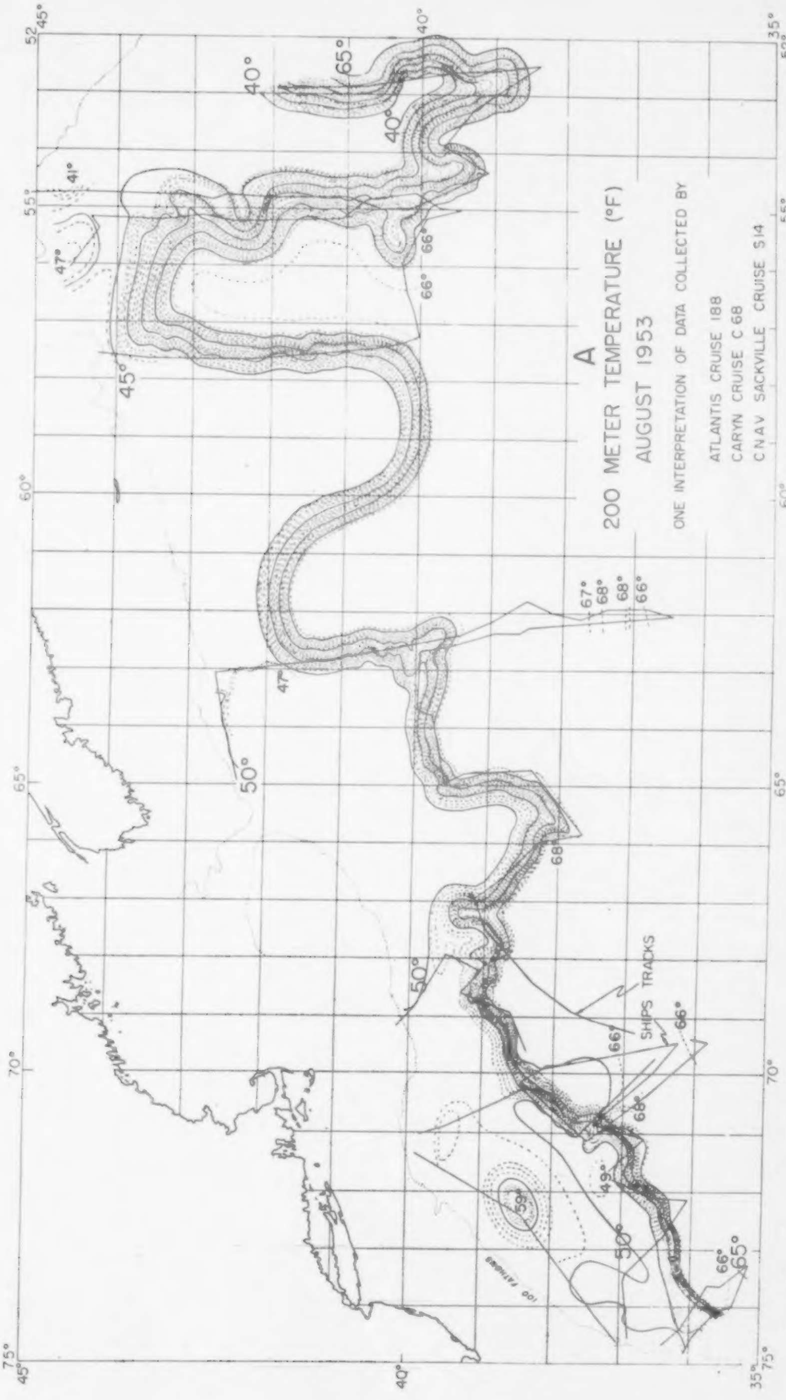


Chart 3a. An analysis of the temperature field (degrees F) at a depth of 200 metres in the Gulf Stream between 75° and 52° West longitude.

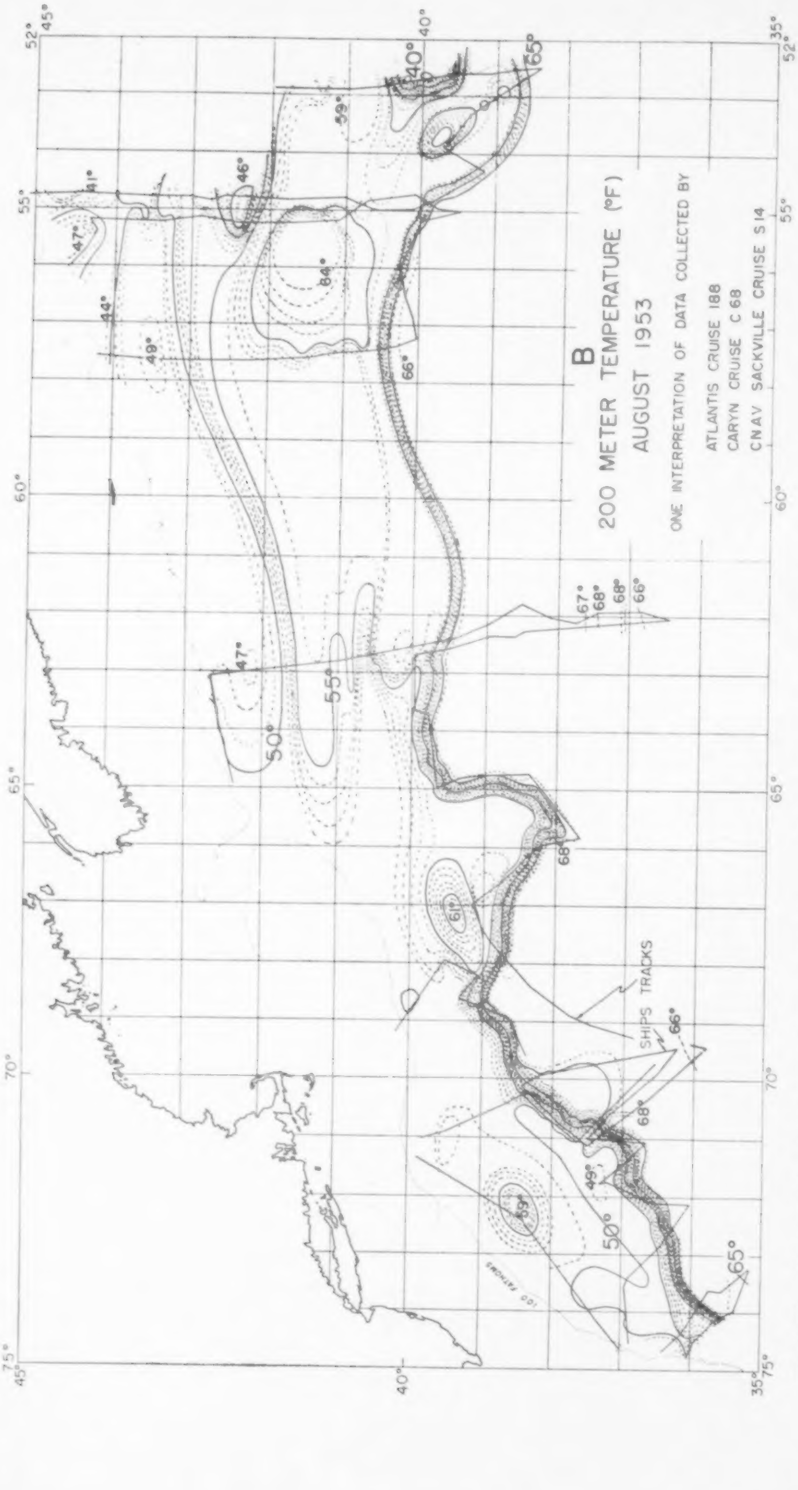


Chart 3b. An analysis of the temperature field (degrees F), at a depth of 200 metres in the Gulf Stream between 75° and 52° West longitude.

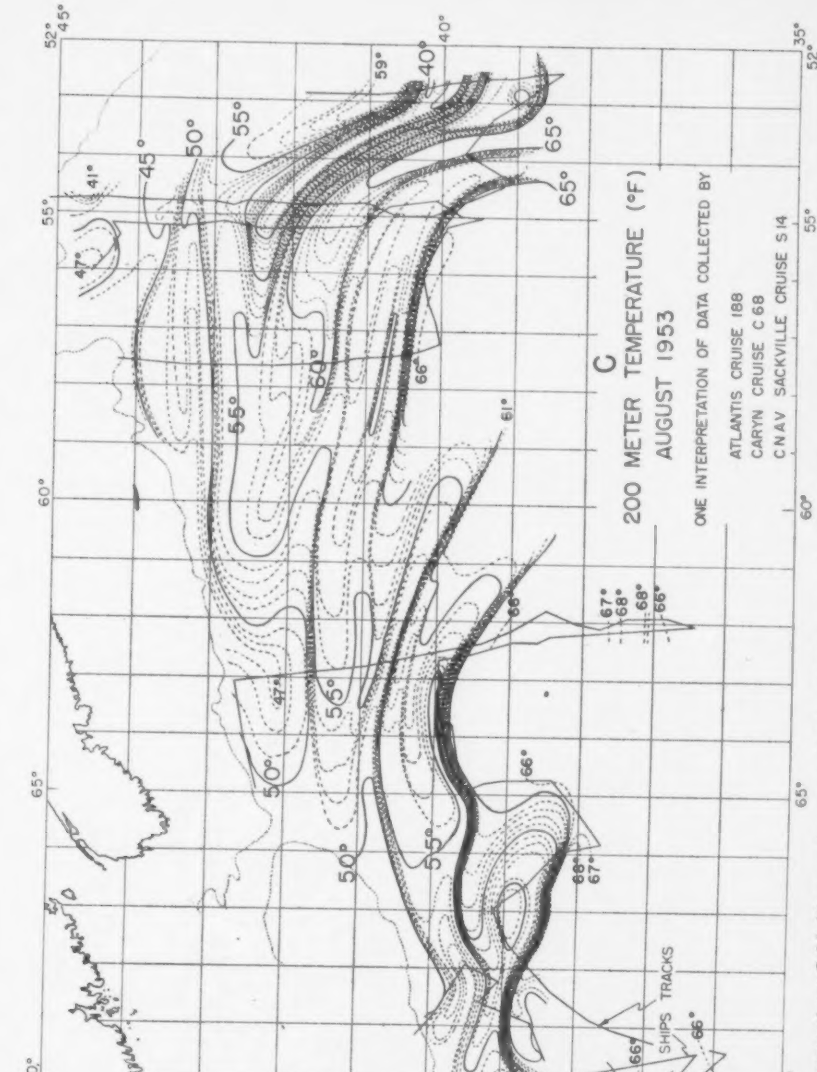


Chart 3c. An analysis of the temperature field (degrees F), at a depth of 200 metres in the Gulf Stream between 75° and 52° West longitude.

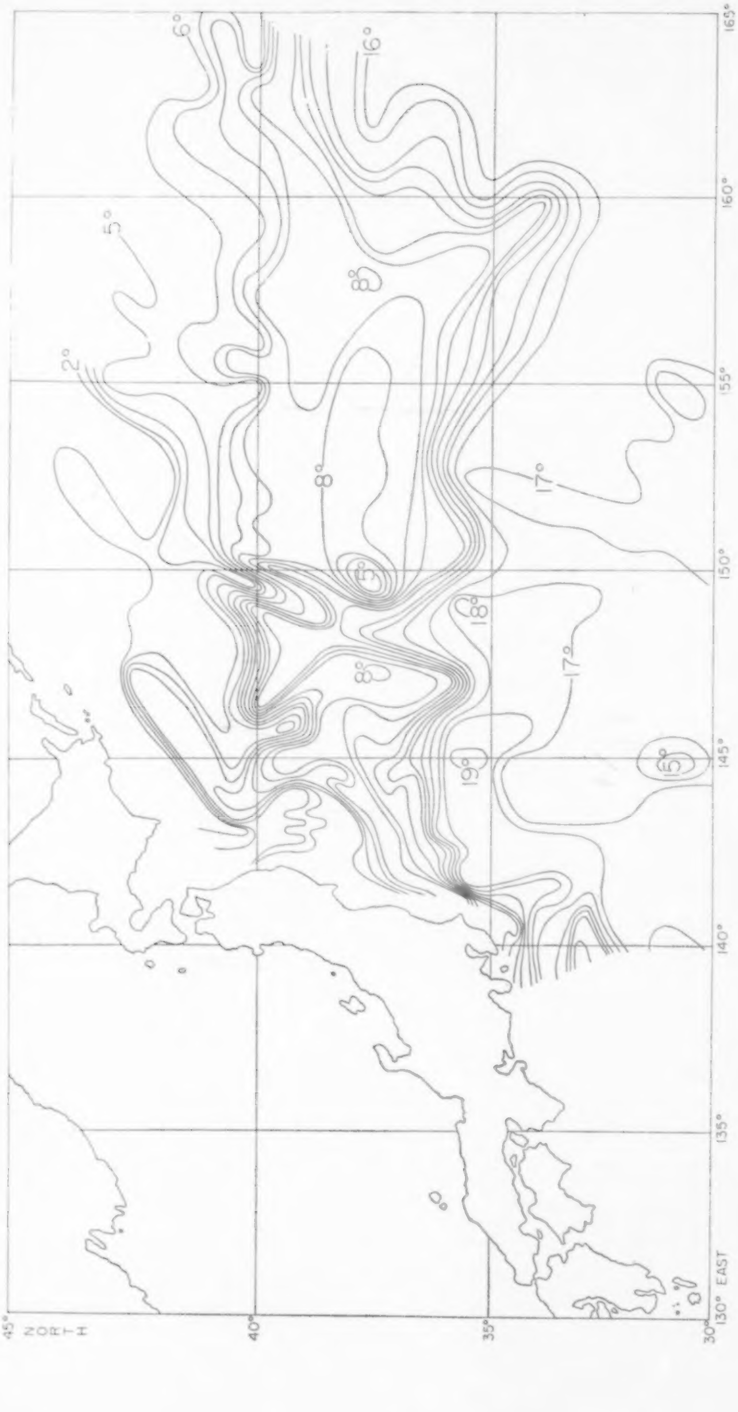


Chart 4a. One analysis of the temperature field (degrees C), at a depth of 200 metres in the Kuroshio System, after UDA (1935). From data obtained by numerous Japanese vessels, 1-14 August, 1933.

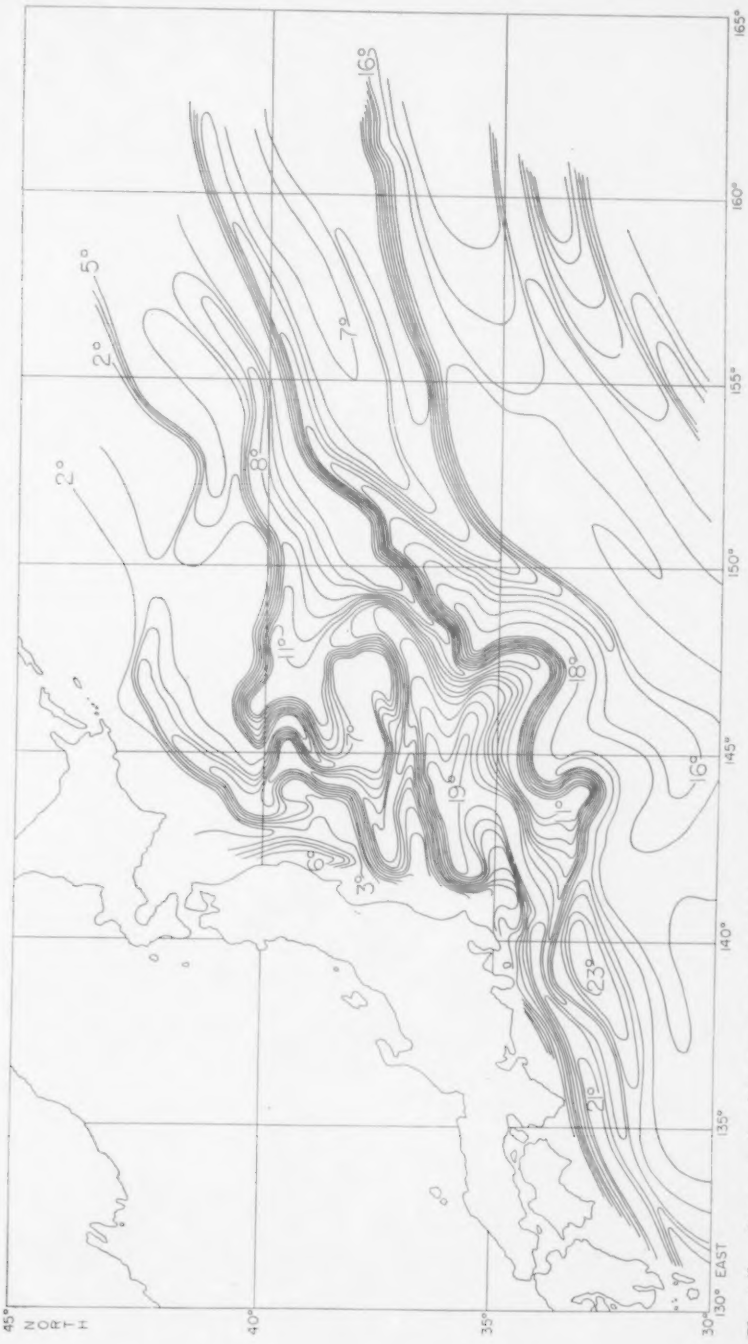


Chart 4b. One analysis of the temperature field (degrees C), at a depth of 200 metres in the Kuroshio System. From data obtained by numerous Japanese vessels, 1-14 August, 1933.

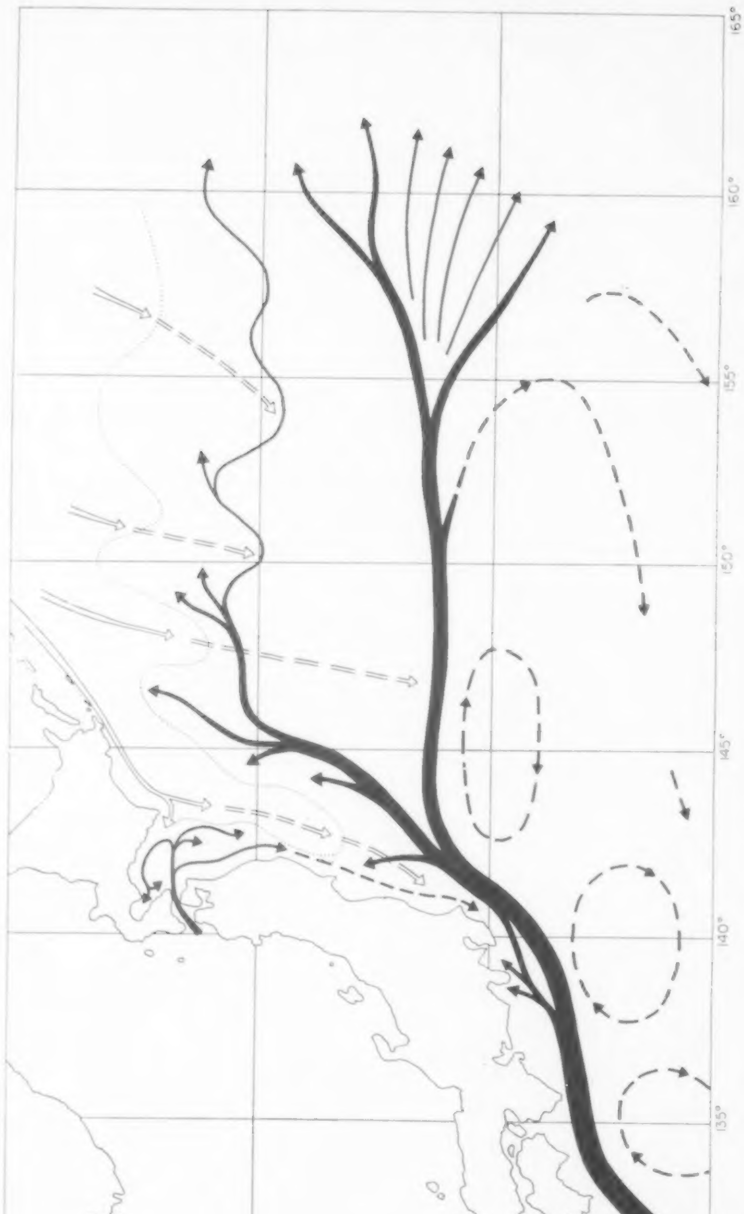


Chart 4c. The currents in the Kuroshio System during August, 1933, after UDA (1935).

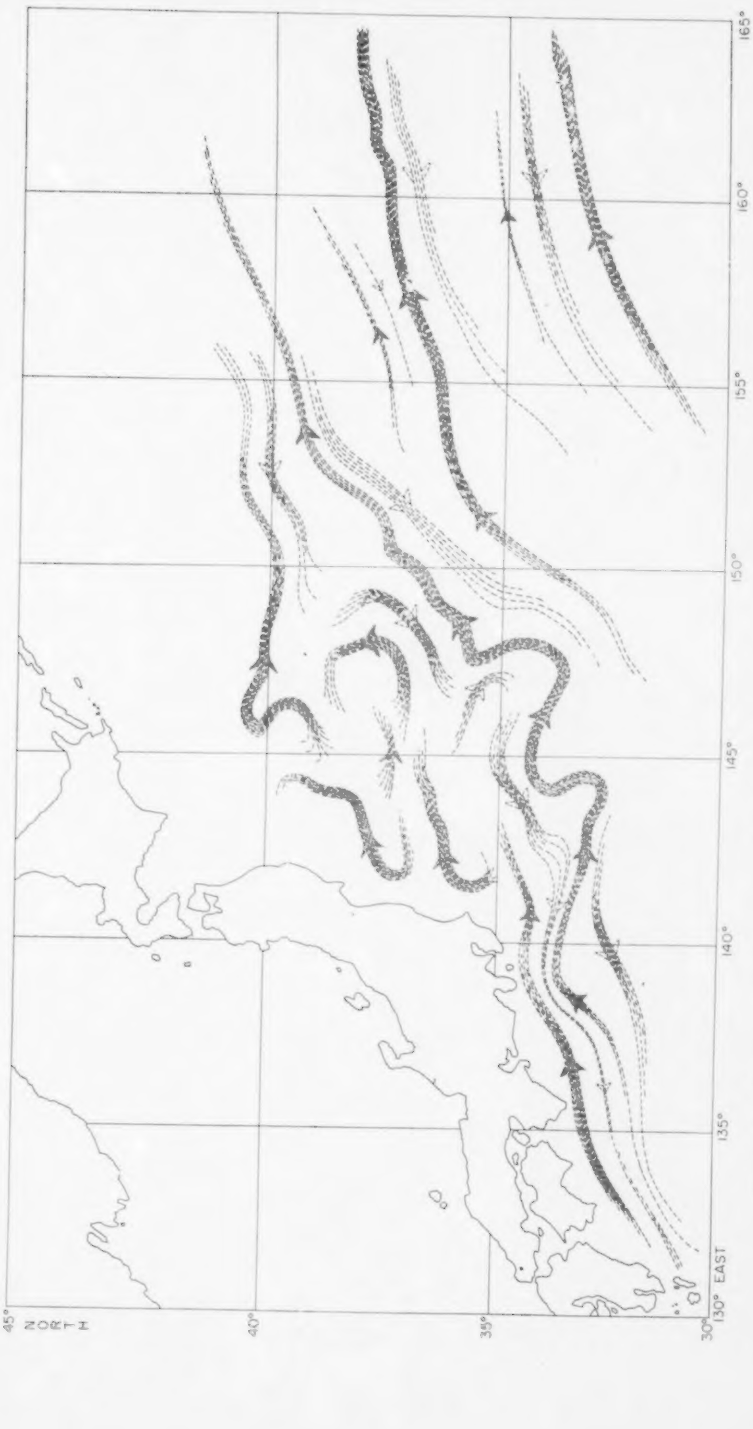
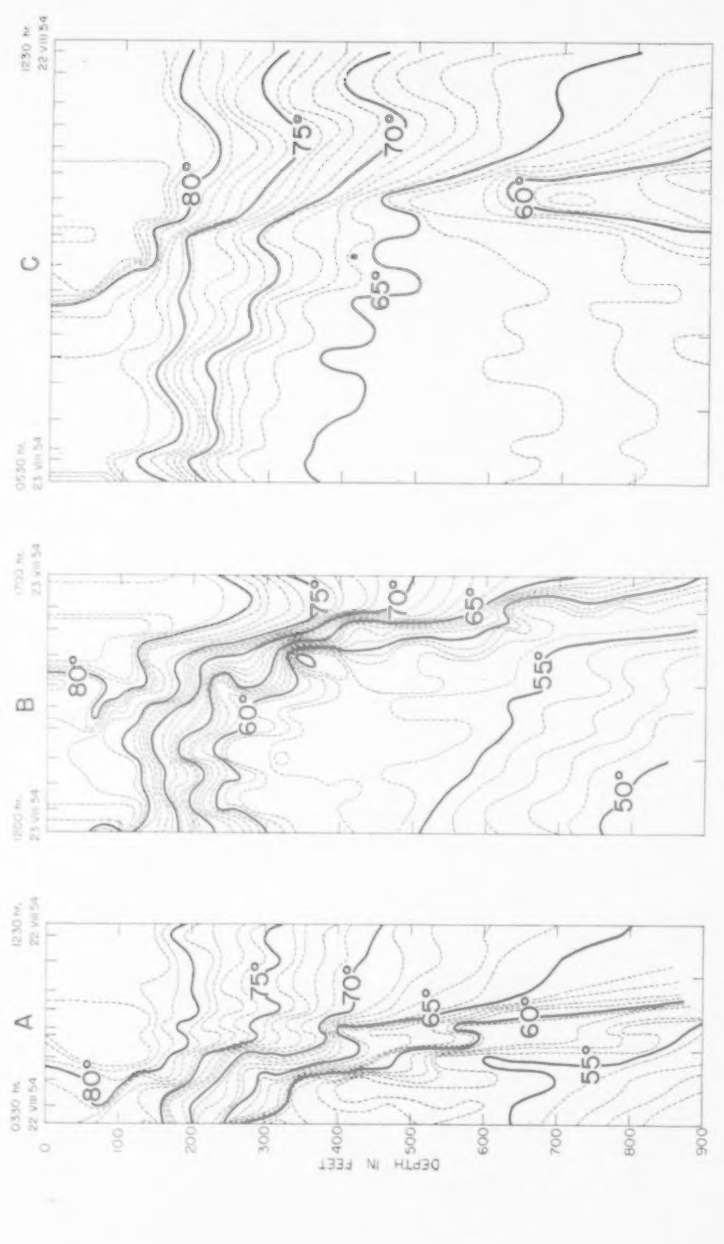


Chart 4d. The currents in the Kuroshio System, based on the 200 metre temperature field shown on chart 4b.


A
B
C
80°
75°
70°
65°
60°
55°
50°
DEPTH IN FEET
0
100
200
300
400
500
600
700
800
900

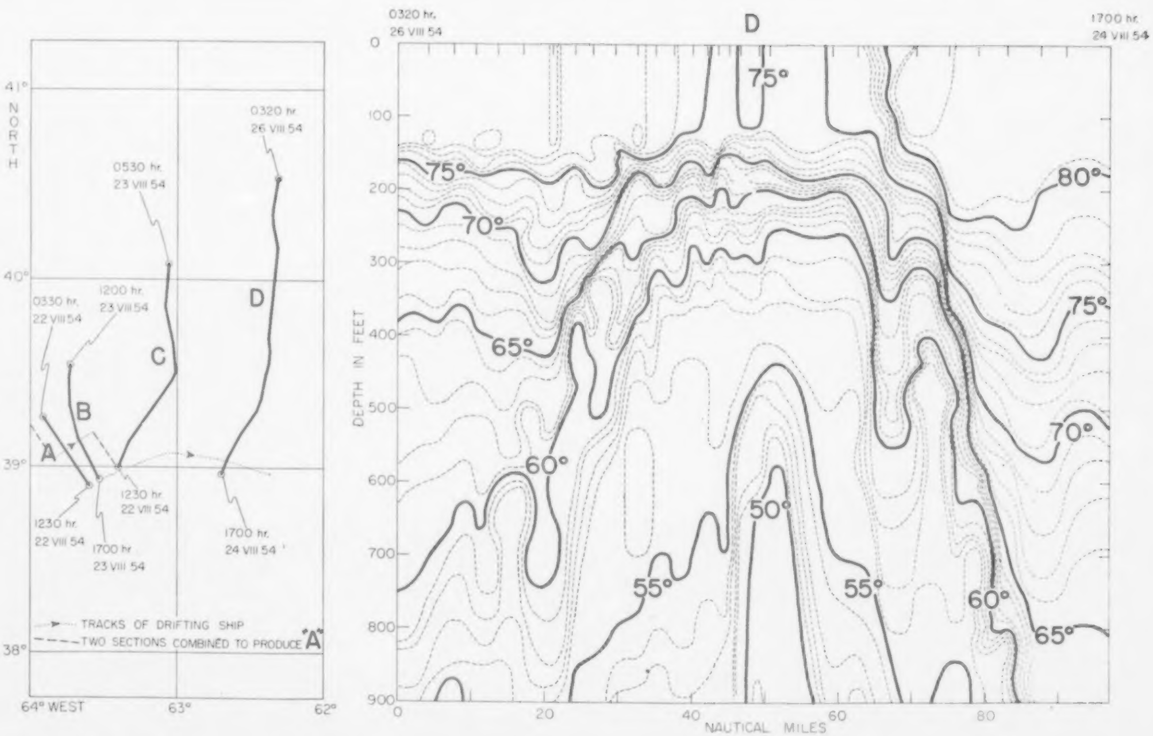


Chart 5. Four temperature-depth profiles in the Gulf Stream System south of Novia Scotia. From data obtained by the Woods Hole Oceanographic Institution Research Vessel *Caryn*, 22-25 August, 1954.

Deep-Sea Research, 1955, Vol. 2, pp. 230 to 246. Pergamon Press Ltd., London.

Magnetic particles found by raking the deep sea bottom

By ANTON FR. BRUUN,* EBBE LANGER§ and HANS PAULY‡

Summary—A collection of strongly magnetic material on the ocean floor was one of the many subjects undertaken by the Danish Deep Sea Expedition – The *Galathea* Expedition 1950-52. In the following a description of the instrument, the magnetic rake, is given by its constructor, A. FR. BRUUN, and the way it was handled on the *Galathea* is mentioned. The description of the material is given by HANS PAULY. His conclusions are further supported by experiments carried out and described by E. LANGER.

The magnetic rake, an oak-board 100 × 15 × 5 cm, carrying 63 magnets in three rows, was drawn along the ocean bottom and is considered to have covered about 45,000 m^2. Apart from insignificant amounts of artificial material and varying amounts of magnetite-sand more than 300 particles of a very remarkable character were obtained. Most particles were spheres with a diameter of less than half a millimetre. A lot of them consist wholly of magnetite, but many have a silicate groundmass loaded with magnetite crystallites. In nearly all spherical cavities occur. Seven metallic particles were found in the material. Those examined were seen to contain: Ni-Fe, carbides, phosphides, etc. The structure and composition of these metallic particles seem to require high temperatures and rapid cooling in the formation-process.

Discussions of similar material from bottom cores taken by the Swedish Deep Sea Expedition, certain features in crusts of two Danish stony meteorites, the whole picture of the material from the *Galathea* Expedition 1950-52 and the *Challenger* Expedition 1872-76 seem to favour the ideas of MURRAY and RENARD. The particles are supposed to represent material torn off from meteors due to air-resistance on their passage through the atmosphere; it only seems necessary to add stony meteorites as an important source.

It is considered convenient to give these particles a special name in order to distinguish them from meteorites and cosmic dust, and it is therefore suggested to call them caudaites.

METHOD OF COLLECTION

THE main purpose of the *Galathea* Expedition 1950-52, The Danish Deep Sea Expedition around the world, was to study the organisms of the great and greatest depths of the ocean (BRUUN 1953). In the programme could, however, be included such other studies which would not to any serious extent interfere with the main purpose and yet contribute to our knowledge of the many problems still hidden in the deep oceans.

The classic studies of MURRAY and RENARD (1891) and their conclusions about the cosmic origin of certain particles in the deep sea deposits suggested to me the possibility of collecting débris from meteors or shooting stars as was the current term onboard.

Considering the slow rate of sedimentation and aiming only at obtaining magnetic particles it was easy to construct a magnetic rake, which could be towed at the same time as our biological sledge trawls of the Sigsbee type.

The magnetic rake (Fig. 1) consists of a solid board 100 × 15 × 5 cm made of oak. A steel wire bridle was fixed to the ends of the board so that the apparatus easily could be attached to one side of the frame of the sledge trawl.

* Zoological Museum, The University, Copenhagen, Denmark.
§ Department of Metallurgy, Technical University, Copenhagen. Denmark.
‡ The Mineralogical Department of the Kryolitselskabet Øresund A/S, Copenhagen, Denmark.

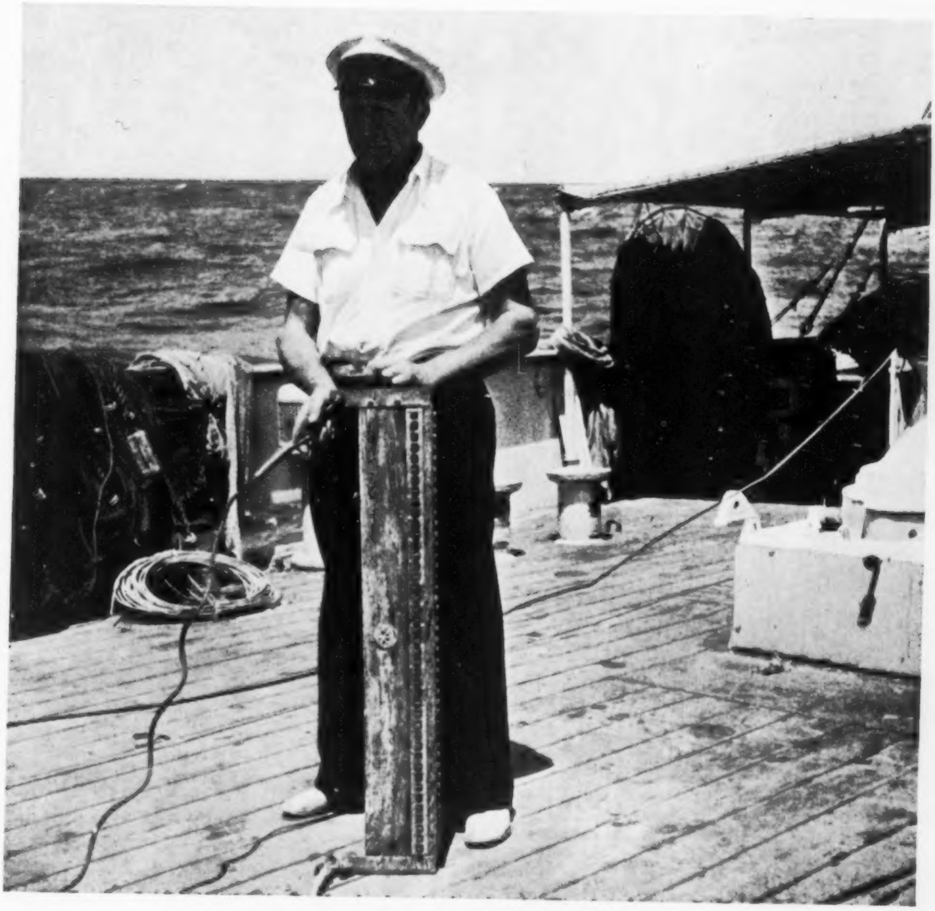


Fig. 1. The magnetic rake. Photo: *Galathea Expedition*.

Along the hind edge of the board and at each of its two broad sides were inserted a row of permanent magnets sunk into the board so that only the free legs of the magnets protruded by 1 cm. The two rows were inserted 3 cm from the hind edge. In this way the rake would work whether it was revolving or not under the lowering of the gear. As a counter weight to the magnetic rake a small biological dredge was placed at the other end of the frame of the sledge trawl.

The protruding parts of the magnets end in smooth, square surfaces, 1 by 1 cm. The distance between distal parts of the poles was about 15 mm, while it was about 10 mm proximally. All the magnets were covered with a very thin layer of copper to prevent corrosion from the salt water.

It must be admitted that the apparatus was just a simple construction, easy to handle, but at the same time it proved to be quite as efficient as we had hoped for. After the two years' cruise it is still as perfect as at the start. When it was not in use a flat rod of soft iron was placed over the magnet poles. No measurements of the power of the magnets have been made but now, after the lapse of four years they appear as efficient as at the start.

The rake was stored in the laboratory and carefully inspected before use; it was not attached to the sledge trawl until this was quite ready to be lowered into the sea. Special precautions were taken that the rake should not touch the deck or side of the ship. The strict routine of the ship, when fishing was going on, was not to throw anything over board, because great care was taken not to contaminate the catches of the often exceedingly delicate organisms.

When the rake came up care was again taken that it should not touch any part of the ship; it was then carried to the laboratory and placed on a wooden table. Then followed the tedious work of cleaning each single of the 126 poles. With dissection lenses fixed before his eyes and both hands free the operator might brush the poles clean of particles with a hair brush and collect them. All that was removed was every now and then washed into a Petri dish filled with 70% alcohol; finally the alcohol was poured away and the residue left to dry and then stored in a glass tube.

It should be emphasised that anything clinging to the magnets was stored; it was left to the geologist to determine what might be ascribed to human activity. Actually we did not expect much contamination from the ship, but in our trawls we very often found macro-sediments like pieces of coal and slags which did not come from our ship, which used fuel oil. This most frequently happened in the shipping lanes, but not always, and again all was preserved for the geologist to determine in the laboratory. Only when we trawled an old-fashioned glass bottle, hand-cast, at 3,620 m there was no doubt about the human origin; but three deep-sea actinians attached to it was the definite proof that the *Galathea* was not involved.

The depths were continuously recorded during trawlings, which were carried out according to the very efficient method developed by KULLENBERG (1951). This means that an even bottom was selected with, at the most, slight variation of depths; therefore the depths given for the *Galathea* stations are the real depths where the rake and trawl were towed at the bottom; this cannot always be said of the depth records from trawlings carried out before the time when continuously recording echo-sounders were invented. The experience of recent years is that an even plain in the ocean is probably no more frequently met with than on land.

However limited the results of our magnetic rakings are, they should stimulate similar work on a large scale; we could have handled a much larger and heavier rake with no difficulty; this would have meant a larger area covered; and more powerful magnets might have increased the effectivity of the instrument; our faint hope of finding nutsized iron lumps was perhaps too ambitious, even if our rake could catch quite heavy objects while we were experimenting on land. But if a suitable area in the ocean could be selected better results might be expected; this would be in places where the light sediments are carried away by the currents, perhaps upon some rise of the bottom. However useful the level bottom was for easy trawling

Table 1. Positions etc. of the material collected by the Galathea Expedition. The percentage of cosmic matter only very roughly estimated. The length of haul given represents a maximum value.

St. No.	Position		Dates	Depth in metres	Bottom preliminary deter-minations	Weight in gr.	Cosmic material (est.)	Black shining spherules	Greyish-brown dull spherules	Reniform & slag-like	Metallic particles	Divers	Est. length of haul (sea miles)
24	3°54′N	8°22′W	15/11/50	3200	clay	(1·84) 0·28	25%	more than 50	more than 20	8	2	a nail, etc.	1·5
30	0°42′N	5°59′W	18/11/50	5160	clay	0·02	90%	not observed	8	0	1	organic remains, etc.	1·5
65	2°17′S	8°10′E	4/12/50	2770	bluish clay	0·05	100%	some few observed	2	8	–	–	1·8
175	35°00′S	27°22′E	21/ 1/51	4390	glob. ooze	0·06	50%	,, ,, ,,	some few observed	8	1	magnetite sand	–
176	35°12′S	27°35′E	21/ 1/51	4350	glob. ooze	0·30	10%	,, ,, ,,	,, ,, ,,	8	–	magnetite sand	1·8
180	34°56′S	36°31′E	25/ 1/51	5220	clay	0·01	100%	,, ,, ,,	not observed	3	–	–	2·5
231	8°52′S	49°25′E	7/ 3/51	5010	glob. ooze	0·93	10%	,, ,, ,,	4	8	1	magnetite sand, much	1·5
233	7°24′S	48°24′E	9/ 3/51	4710	glob. ooze	1·56	1%	,, ,, ,,	some few observed	4	–	,, ,, ,,	0·6
279	1°00′S	76°17′E	8/ 4/51	4300	glob. ooze	0·15	75%	more than 15	more than 20	5	2	organic remains, etc.	1·2
408	12°47′N	116°24′E	4/ 7/51	4330	glob. ooze	0·36	100%	not observed	not observed	8	–	–	3·0
574	39°45′S	159°39′E	18/12/51	4680-4730		1·80	50%	more than 50	more than 20	6	–	magnetite sand	3·6
599	45°47′S	164°39′E	13/ 1/52	4320		0·43	5%	not observed	not observed	2	–	magnetite sand, much	3·5

for animals we were well aware of the fact that it might not give as good a result in the case of the magnetic rake. (A.B.)

GENERAL DESCRIPTION OF SAMPLES

The samples are surprisingly free from artificial products. Only in the sample from station 24 material of an undoubtedly artificial character was found: A nail and some chips of common iron 1-2 cm across. In the samples from station 231 and station 233 some very thin and small rusty wire-like pieces were found. They were half a cm long and 0·1 mm thick. Besides indeterminable pieces of rust were seen in some of the samples.

Several of the samples contain relatively large amounts of magnetite sand consisting of fragments of magnetite crystals. A few small lumps of clay, a few rounded silicate grains, and pieces of organic origin – fragments of shells, fish scales, etc. – have also been observed in the samples.

In all the samples odd particles are found. Odd because they have an appearance quite unlike anything one might expect. They are odd in another respect too because they form the constant and characteristic element of all samples. These odd particles are easily divided into a few groups by means of their macroscopic appearance, or rather their appearance when examined with a lens as most of them have a diameter of less than 1 mm (Fig. 2).

The most conspicuous of these particles are reniform and slag-like greyish to greyish-brown. Of the odd particles these are the biggest, one of them being $3 \times 4 \times 8$ mm. Most of them, however, are about 1 to 2 mm. They are found in all the samples, from two to eight in each. More than 50 have been found altogether.

Two other groups of odd particles are pretty remarkable on account of their shape. They are almost perfect spheres. The spherules in the first of the groups are greyish to greyish-brown like the reniform and slag-like particles. They may be 1·5 mm in diameter, but generally they are a little less than 1 mm. They are dull and often present rough surfaces. Now and then tiny spheres may be observed on the surface. In a few cases two such spherules have formed one irregular particle. Such forms may be interpreted as indicating a close connexion between these particles and the reniform ones. In all the samples nearly 100 of these particles have been found.

The other type of spherule consists of black shining spheres of fairly small dimensions. The biggest one has a diameter of about 0·5 mm but most of them are less than 0·2 mm, the greater part having a diameter of about 0·1 mm. The colour is similar to that of magnetite, the shape a perfect sphere, but in most of the spherules may be seen a little depression or a flattering, sometimes it is obviously a hole leading to an empty interior. This type of particle has been observed in samples from 8 stations in some of which they occur in very great numbers, while in others few were seen. It is, however, the type of particle which occurs most frequently, in all the samples over a hundred have been counted.

The most interesting type of particle, however, is represented by 7 particles from 5 stations. Two of them are spheres and the others have various rounded forms. The diameter of the largest is about 0·5 mm and of the smallest about 0·2 mm. Their colour is a light metallic grey with a faint yellow-rusty hue like stains here and there. These metallic particles are rather remarkable as they are not actually rusty.

The widespread occurrence and the uniformity of the particles give them an outstanding position among the sediments from the deep sea bottom. It seems obvious that they have been formed in a particular manner. The quantity of material from the different stations is rather small and it was accordingly not considered possible to carry out quantitative chemical analyses. In order to save as much material as possible it was decided to examine the grains by means of an ore microscope. The single grains were imbedded in plastic and polished according to the low relief method on lead laps. In accordance with the results of these examinations some grains were selected for chemical tests, and some particles were used to make powder preparations in order to determine the non-opaque minerals present.

THE RENIFORM PARTICLES AND THE DULL SPHERES

On examining these particles in the polished sections it appears that they consist of two major components: A silicate ground-mass with magnetite crystals or crystallites. Figs. 3, 4, and 5 illustrate some of these structures. The ratio between the two components seems to vary to some extent and this fact seems to influence the colour of the particles.

The silicate mass is now and then built up of lathlike minerals as appears from Fig. 5. The refractive index is assumed to be about 1·65 or more as judged from the reflection colour.

Some spheres were crushed and examined microscopically. Most of the silicates are so heavily pigmented that it is almost impossible to determine the minerals. At least two minerals were seen to be present: One with a refractive index of about 1·63 and with a low birefringence, it looked like apatite, but it proved impossible to determine it more closely. The other mineral, representing the major part of the silicate minerals found, has a refractive index of about 1·66 and a birefringence of the same magnitude as quartz. Some of the grains of this mineral were rectangular with parallel extinction. A pronounced zonal growth was observed in two grains. It seems to be a rhombic pyroxene. The material in question was selected from the sample from station 279.

As appears from the pictures in Fig. 5 the magnetite may show zonal growth with a darker central part. The magnetite is often observed as star-shaped skeletal crystals. Optics and hardness generally correspond with magnetite, but here and there the grains may be observed to be clearly anisotropic. The zonal development seems to indicate that the mineral holds a certain amount of foreign matter, e.g. spinel molecule, which was originally dissolved but on cooling separated, and owing to the rapidity of cooling this exsolution did not form well developed crystals. In some cases where the magnetite occurs as more compact masses the mineral may show a distinct anisotropy. This is seen, for example, in the magnetite pictured in Fig. 5. The picture represents the outer part of a particle. In the periphery some hematite appears and between this mineral and the inner part of the particle a zone of more compact magnetite is seen grading into the disseminated magnetite in the interior. The compact magnetite shows anomalous anisotropy. The occurrence of hematite in the outer part of the particle is not limited to this particle. It has been observed in many of the particles of that description as well as in the other magnetite containing particles. Sometimes the hematite forms lamellae in the magnetite, sometimes it is seen as in the case in Fig. 5. But it always occurs in the periphery of the particles.

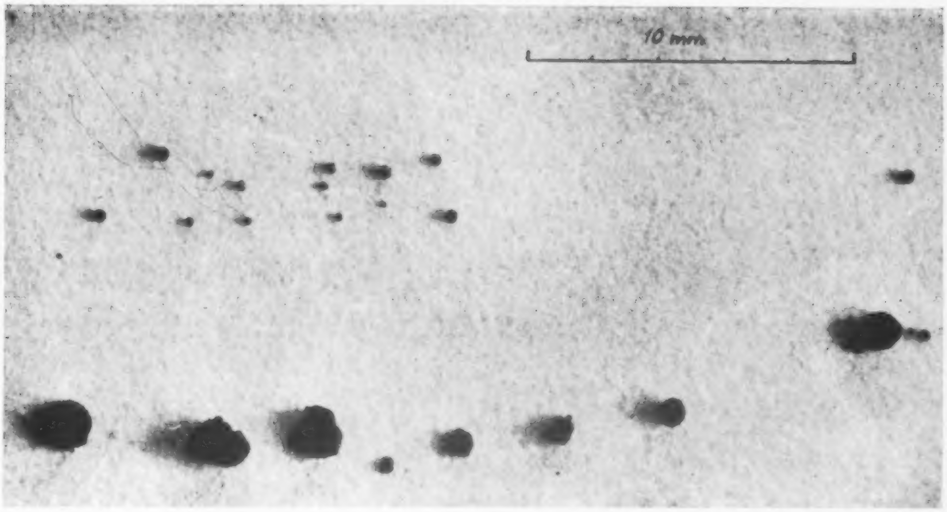


Fig. 2. Particles from station 279; the largest are reniform and slag-like particles, No. 5 from left in the bottom row is a dull greyish-brown spherule. The small spherules are black shining spherules but the largest among them may be silicate spheres with a compact mantle of magnetite. Photo: H.P.

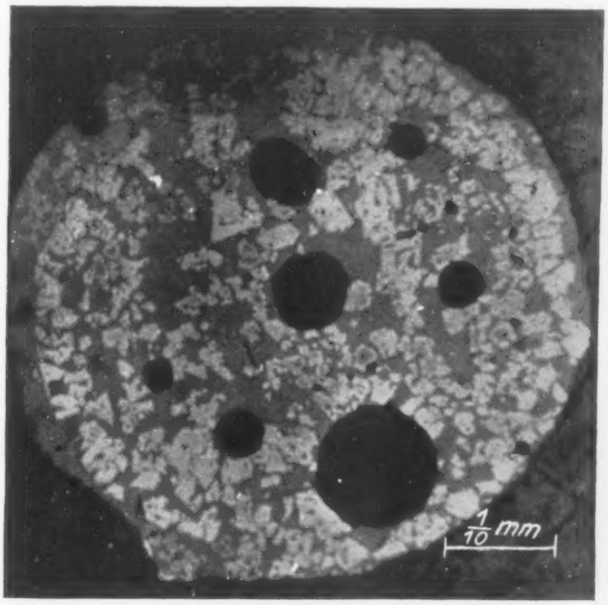


Fig. 3. Silicate sphere or dull greyish-brown sphere with magnetite crystals. Several cavities are seen in the particle. Polished section. Photo: H.P.

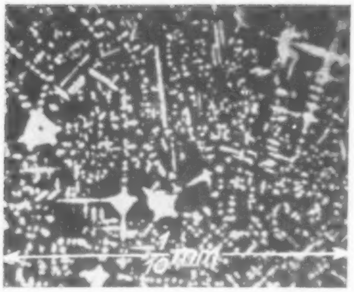


Fig. 4. High-magnification view of the magnetite crystals in silicate in a dull greyish-brown sphere. Polished section. Photo: H.P.

Fig. 6. Compact magnetite with sulphide included between the grains. The sulphide is thought to be pentlandite. Polished section. Photo: H.P.

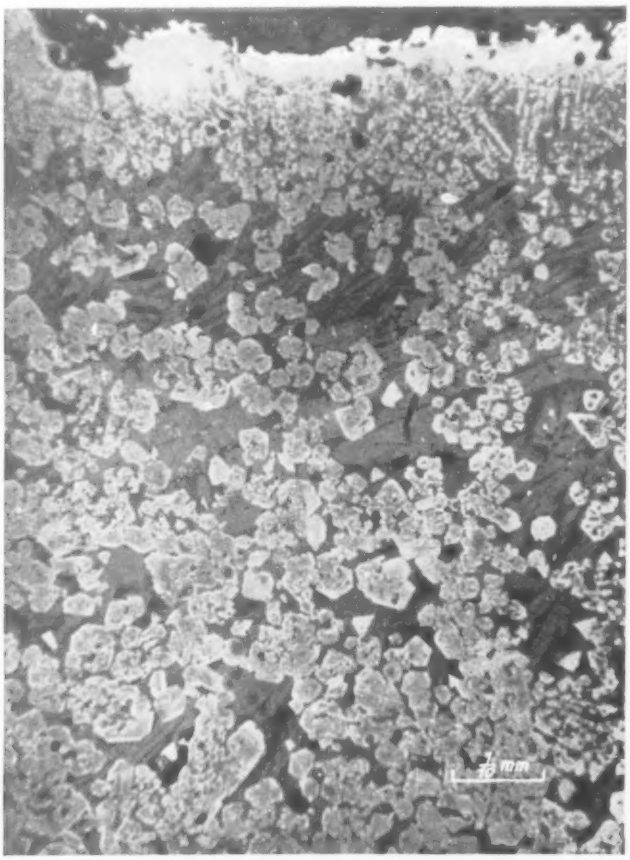


Fig. 5. Magnetite crystals showing zoned development in silicate groundmass with two components. The uppermost part is the periphery of the particle. Here the magnetite is compact and anomalous anisotropic. Against the plastic (dark grey) the surface layer of the particle is seen. Here the magnetite is replaced by hematite, whitish. Polished section. Photo: H.P.

A small silicate sphere only some hundredths of a mm in diameter, contained magnetite as very small inclusions regularly distributed in three directions, probably according to the crystal structure of the silicate mineral.

The spherule pictured in Fig. 3 shows several rounded cavities in fact a very common feature in these particles and may be considered characteristic of them. These cavities vary greatly in size, sometimes they may be so large that they make the particle look as if it were built up of a few sphere shells. It is to be assumed that such particles represent a transitional form between the reniform or botryoidal particles and the slag-like ones.

In some of the cavities a compact mass of an amorphous looking material may be observed which possibly is volcanic glass. In a sample from station 24 a single grain of a metallic matter in the glasslike material was observed. The grain was less than 5 μ. The colour was white and the grain seemed isotropic, the reflection was very high and comparable only with metallic iron or the like.

From station 574 a fairly great number of the dull greyish-brownish spheres are to be found in the sample. A characteristic particle of this type was chosen in order to look for Ni in it. Nickel was not found.

On examining two dull greyish spheres from station 279 several minute grains of sulphides were observed. In both spheres the silicate mass is heavily crowded with magnetite crystals, and in areas this mineral forms a compact mass with a granular structure. In such an area sulphide is found as shown in Fig. 6. The sulphide is creamy white and isotropic with a hardness distinctly lower than magnetite. The mineral is supposed to be pentlandite, but daubreélite as a possibility should not be excluded. The shape of the grains, clearly intergranular, is totally determined by the surrounding magnetite.

In an area with lots of magnetite crystals in the silicate mass another sulphide was found. Unlike the former sulphide from the other sphere this mineral was clearly anisotropic. Colour and hardness correspond well with pyrrhotite as does the effect of anisotropy, and it therefore seems likely that it actually is this mineral.

In the sphere with the anisotropic sulphide was found a grain with very high reflection. It must be a metallic phase but it was impossible to determine it more closely.

THE SLAG-LIKE PARTICLES

In most cases the difference between these and the above mentioned particles is the greater number of cavities in the former. They are decidedly porous. Otherwise they are built up of silicate and magnetite crystals like the dull spheres.

In a few of these particles the magnetite crystals were found in a groundmass of a semi-opaque character. This material has a colour almost like hematite, but it is highly varying from place to place and gives the area a mottled look. The material has very pronounced internal reflections, the colour is red to reddish-brown.

Two particles from different stations were analysed for Mn but this element was not found. A big particle, from station 408, was in the same manner examined for Mn. The particle weighed 0·174 g and in this 0·6% Mn were found. In the same particle no Ni was found.

The mottled material substituting the silicate mass in some particles from station 279 and occurring in small amounts in other particles may presumably be hydrous

iron oxides. Some 20 particles have been examined either microscopically or chemically, none of them may be suspected of containing sufficient Mn to be classified as manganese nodules.

THE BLACK SHINING SPHERULES

Fig. 7 illustrates the common appearance of a polished section of the above type of particles. It is in most cases only a shell of magnetite in a compact granular form. In the outer part of the magnetite shell hematite lamellae have sometimes been observed.

In some of the polished sections of these particles the magnetite showed a finely developed polygonal structure the single grains in it being separated by minute cracks, The magnetite itself was very often seen to be clearly anisotropic. The single grains were thus observed to be built up of several individuals, often irregular but sometimes lathlike. Judging from the general appearance and the properties seen against the hematite it seems safe to assume that it is anomalous magnetite.

Some of the black shining spheres selected for polishing turned out to be silicate spherules with magnetite crystals. The magnetite formed in the outer part of the particle a compact mass thus giving rise to the same macroscopic appearance as the black shining particles.

THE METALLIC SPHERULES AND PARTICLES

In two cases metallic grains have been found in the particles just described. As both of them were exceedingly small only the metallic character could be observed. Of the seven metallic particles found in the samples three were polished: One from station 24, one from station 30, and one from station 279.

It should be mentioned that further two metallic particles, not included in the 7 mentioned, were polished. As they showed a common pearlitic structure and qualitative tests for Ni were negative they were considered artificial. The more so as they occurred covered with a thick rusty crust in contradistinction to the other metallic particles to be discussed below.

THE METALLIC SPHERULE FROM STATION 30

The particle is a perfect sphere with a diameter of about 0·4 mm. Under the microscope the material is seen to be built up of two metallic phases, a lighter dendritic component with a darker interdendritic mass. The dendritic phase is white with a very faint creamish hue. It may easily be scratched by a needle, the hardness may be approximately the same as that of metallic iron. Between crossed nicols it is seen to be isotropic. The material was not affected when the specimen was etched with diluted aqua regia. The interdendritic mass is slightly darker with a greyish hue against the other component. The hardness may be about the same as that of the lighter component, but it is difficult to judge owing to the narrowness of the areas of the component. It is distinctly anisotropic as is seen between crossed nicols. Etching with diluted aqua regia produced a picture as that seen in Fig. 13(*a*), which shows that the darker component was clearly attacked by the reagents.

A few laths of graphite were observed in the outer part of the spherule. In the interdendritic phase minute black spots may be observed here and there as a pigment. It was not possible to determine the character of the material present. A

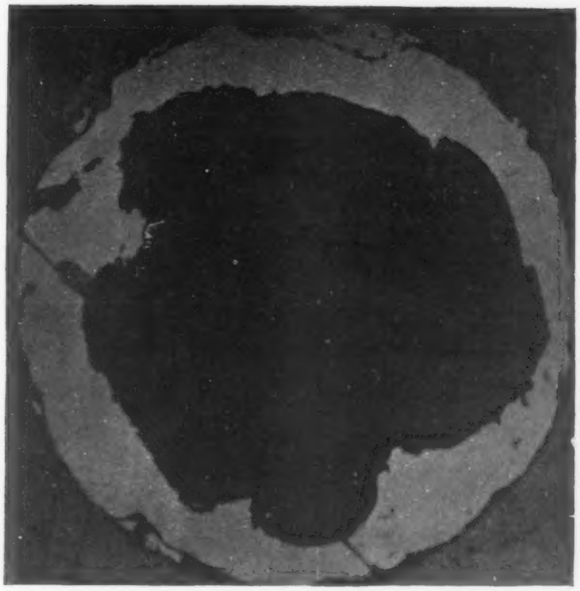


Fig. 7. Polished section of a black shining sphere which is hollow. The shell is magnetite. Diameter 0·5 mm. Photo: H.P.

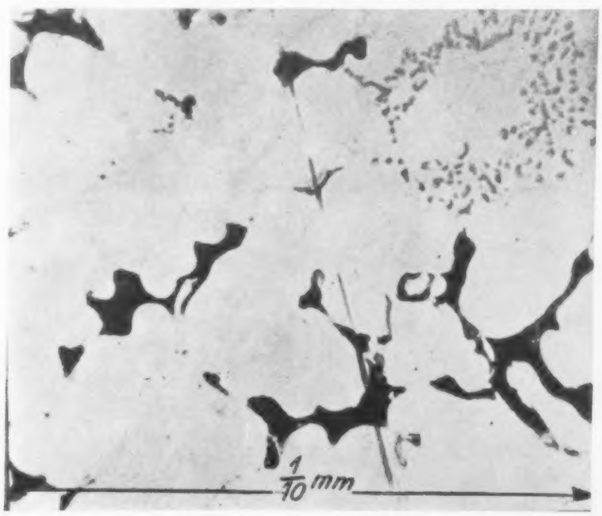


Fig. 8. Cavities left after the interdendritic carbide mass of the metallic particle from station 30. The white areas are nickel-iron. Polished section. Photo: H.P.

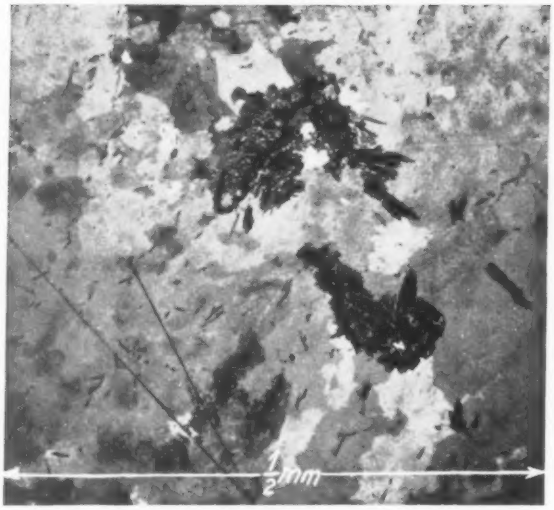


Fig. 9. Polished section of the phosphide-containing particle from station 279. The nicols are nearly crossed. The anisotropy of the components is apparent from the mottled look of the section. The black areas consist of iron-phosphide which happened to be in a total extinction-position to the nicols. The small black streaks are inclusions in the main components. The area 1 cm from the lower edge and 1 cm from the middle line of the picture is seen in high magnification on Fig. 10. Photo: H.P.

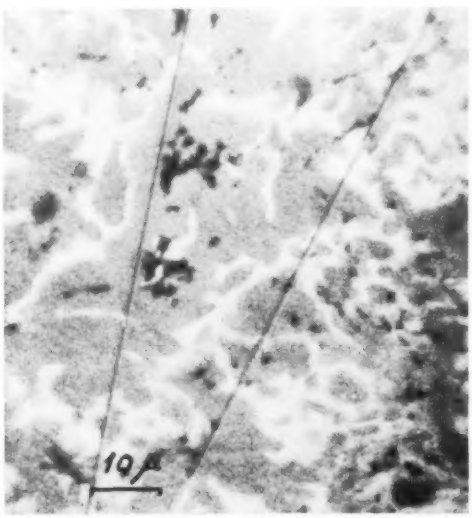


Fig. 10. The darker grey is iron phosphide and the whitish component may be iron carbide. The contrast between the two phases is greatly increased by hard development. Polished section, magnification 900 ×, one nicol. Photo: H.P.

few of the black stains seemed to be graphite, and several of them just looked like holes.

In two areas of the sample we find an appearance like that shown in Fig. 8. Here the greyish interdendritic component has disappeared and most of the black in the figure is only cavities in the shape of the darker component. A few small hard grey grains were seen in these cavities. They seem to be magnetite.

THE METALLIC SPHERULE FROM STATION 24

The only difference between this particle and the metallic sphere from station 30 is due to the fact that the greyish interdendritic component has been replaced by a dark grey matter which is semiopaque. It seems to be limonite or something like it. The number of cavities appearing in the place of the interdendritic mass was greater than in the sphere from station 30.

As the two particles were so similar that from station 24 was used for a qualitative test for Ni. This element was found, together with iron.

The dendritic phase is accordingly supposed to represent a solid solution of nickel and iron; the interdendritic mass may be carbides. The binary structure found in the two particles may thus be taken to represent a primary iron-nickel solid solution with interdendritic eutectic carbide structure. This interpretation also seems in conformity with the experiment which is to be described below.

THE METALLIC PARTICLE FROM STATION 279

This particle is triangular in the section though with rounded corners. The diameter is about 0·8 mm. It is built up of a binary structure with a few minor components included in the two phases.

One component of the binary structure is white. The hardness is pretty great as it cannot be scratched by a needle. Whether it is anisotropic or not is almost impossible to decide, but it seems most reasonable to assume that it is faintly anisotropic (see Fig. 9). The other component is greyish with a high reflection-capacity. The hardness is about the same as in the case of the other component. The colour of the substance is highly dependent on the position to the plane of polarization of the light: it shows very pronounced pleochroism. The darkest position is about as dark as magnetite, whereas in the lightest position it is greyish white or almost as light as the other component. Between crossed nicols it shows as strong an anisotropic effect as, for example, pyrrhotite. The substance thus seems to be iron phosphide and probably it must be assumed that the lighter component is the iron-carbide cohenite or cementite. Neither of the phases was affected when the specimen was etched with diluted aqua regia.

Scattered in the metallic phases many tiny black needle-like inclusions occur, as seen in the photographs Figs. 9, 10 and 12. It proved impossible to get an impression of what sort of material they consist of.

Graphite is to be found here and there, especially in the border-zone of the particle, see Fig. 11.

A very interesting inclusion material occurs particularly together with the graphite lamellae in the outer part of the particle, but single grains of the material have also been found in the central part. As is seen in Fig. 11, the prevailing forms are squares, rectangles and triangles. The material shows a pronounced relief in spite of the

polishing-method which normally gives a very low relief, as in the case of intergrowth of magnetite and pyrrhotite. The hardness must be exceedingly great, even in comparison with phosphide and cohenite. The grains are big enough to permit observations of anisotropy, but the material seems perfectly isotropic. The colour of the grains is gray though not as dark as the darkest position of the phosphide. It seems most natural to assume a very special kind of carbide. Titanium carbide occurs in a similar manner in artificial samples of Ti-containing cast irons, and perhaps the material is identical with or a variety of this compound, known as the meteoric mineral osbornite. A golden-yellow or golden-orange lustre of the central part of the grains seems to be characteristic of this mineral and the artificial compound. This feature has not been observed in the grains of the particle from station 279.

A single grain found in the periphery of the particle seems to be quite important; it is shown in Fig. 12. It is beyond doubt a silicate, and it seems to have a refractive index about that of pyroxenes judging from the reflection of the grain. The shape may be interpreted as an indication of the crystal being rhombic. Thus it looks as if the mineral is either a rhombic pyroxene or olivine.

A survey of the results obtained by MURRAY *and* RENARD *by examining magnetic particles from the deep-sea deposits procured by the Challenger Expedition* 1872-76

In the bottom-samples two different kinds of magnetic spherules were found: Black magnetic spherules with or without a metallic nucleus and brown-coloured spherules resembling chondres with a crystalline structure.

The black magnetic spheres rarely exceed 0·2 mm in diameter. They are black and shining and as a rule have a circular depression. The surface is not perfectly smooth, it looks porous. In some cases two particles are coupled together, one of them is much smaller than the other. When the spheres are broken they are often seen to contain a nucleus of a metallic nature. The metal in the central part may be native iron or an alloy of iron with nickel and cobalt, or it may be schreibersite.

These particles are regarded as cosmic bodies that must be grouped with the holosiderites. Superficial fusion and oxidation is supposed to have taken place in the atmosphere at a very high temperature, and on account of the small size of the particles they assumed a spherical form. The contraction of the superficial crust on cooling would lead to the formation of the cupule as stated in the Report from the Expedition.

The brown-coloured spherules or chondres rarely attain a diameter of 1 mm, their mean diameter may be about 0·5 mm. They are yellowish or brown with a pronounced bronze lustre. Microscopically the lustre is seen to be caused by a finely lamellated structure. If the cupule is found it is generally rather flat. Si, Al, and Mg were observed in these particles. Opaque inclusions are numerous. They are supposed to be titaniferous magnetite. A micropicture shows these inclusions to occur oriented in the silicate material, which is stated to crystallize in the monoclinic system. Character and occurrence together with the black spherules seem to favour a cosmic origin of these particles too.

Magnetic or cosmic particles were found in greatest numbers in the Red Clays of the Central and Southern Pacific. When the mangetic material was extracted from a quart of the clay from these regions twenty or thirty black magnetic spherules and five or six brown spherules were generally found. In the same sediments manganese nodules always occurred as well as organic remains, much altered volcanic lapilli and as a rule crystals of phillipsite.

In globigerina Ooze, Pteropod Ooze, Diatom Ooze, Blue Mud or other terrigenous deposits none or few spherules were found. These deposits are not totally devoid of them. It is therefore to be supposed that the particles are universally distributed, but they are concealed in places where the sedimentation-rate is high.

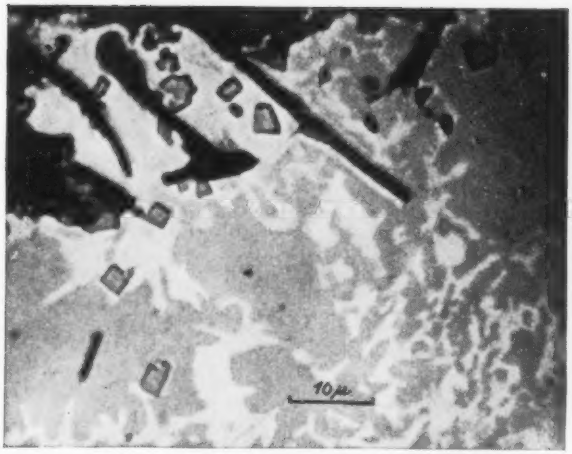


Fig. 11. Peripheral part of the phosphide-containing particle from station 279. Several lamellae of graphite and angular crystals of the osbornite-like mineral are seen. Their high relief illustrates the extraordinary hardness of the crystals. Polished section, one nicol. Photo: H.P.

Fig. 12. Peripherial part of the phosphide-containing particle from station 279. Inclusion of a silicate crystal with rhombic shape. The black area is plastic. Black streaks of an unidentified substance. Polished section. Photo: H.P.

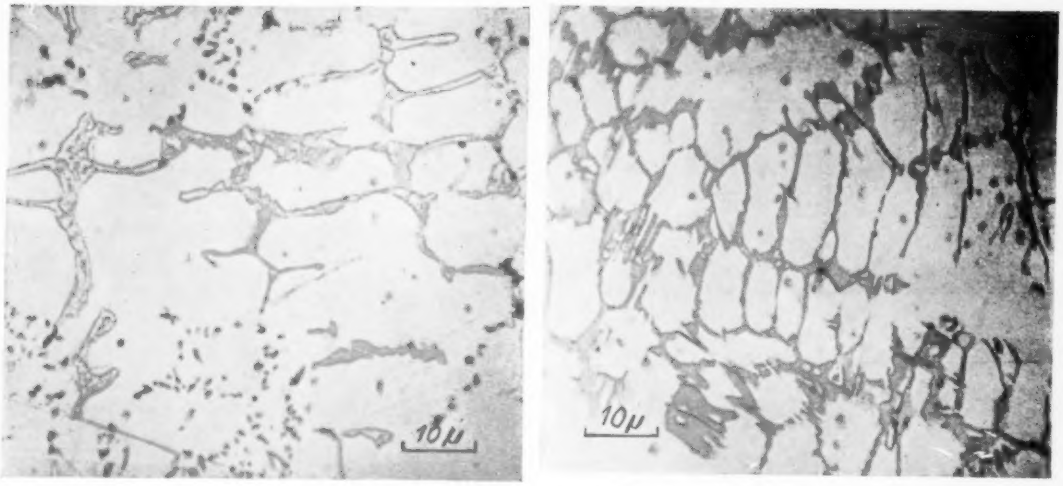


Fig. 13. (*a*) Polished section of the metallic particle from station 30; etched with aqua regia; magnification × 1,000; (*b*) polished section of artificial nickel-carbide interdendritic in iron-nickel; etched with agua regia; magnification × 1,000. Photo: H.P.

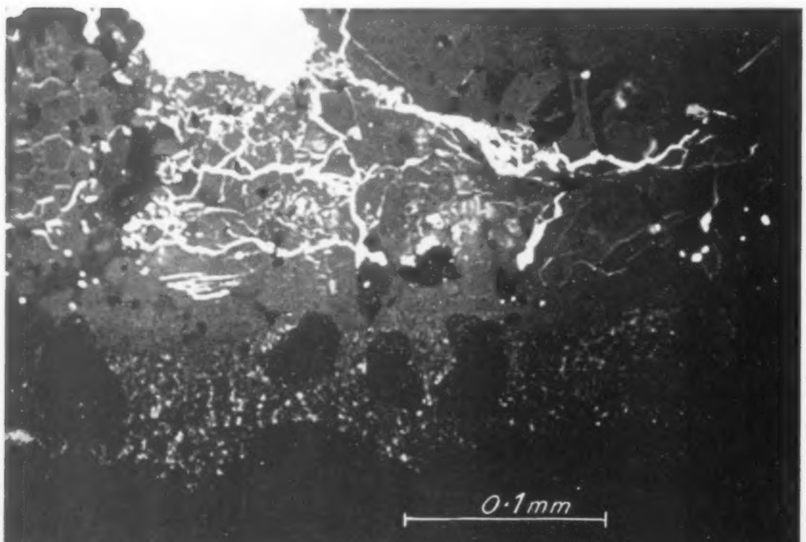


Fig. 14. The outer crust of the Mern Meteorite. In the lower part silicate mass with magnetite crystals, and in the upper part the zone of veins mostly sulphidic material (white). Polished section. Photo: H.P.

The final conclusion is that the particles found may be looked upon as extra-terrestrial bodies allied to meteorites, and in all probability thrown off by them in their passage through the earth's atmosphere.

Table 2. Positions, depth and bottom where the Challenger Expedition found magnetic particles or spheres.

Station No.	*Positions*	*Depths in fathoms*		
157	53°55′S 108°35′E	1,950	Diatom. ooze	few magnetic particles
160	42°42′S 134°10′E	2,600	Red clay	magnetic spherules
209	10°14′N 123°54′E	95	Blue mud	magnetic particles
225	11°24′N 143°16′E	4,475	Radiol, ooze	bronzite spherule
235	34° 7′N 138°00′E	565	Green mud	magnetic particles
244	35°22′N 169°53′E	2,900	Red clay	cosmic spherules
252	37°52′N 160°17′W	2,740	Red clay	cosmic spherules
265	12°42′N 152° 1′E	2,900	Radiol, ooze	magnetic spherules
274	7°25′S 152°15′W	2,750	Red clay	magnetic spherules
276	13°28′S 149°30′W	2,350	Red clay	magntice spherules
282	23°46′S 149°59′W	2,450	Red clay	magnetic particles
285	32°36′S 137°43′W	2,375	Red clay	cosmic spherules
286	33°29′S 133°22′W	2,335	Red clay	magnetic spherules
287	36°32′S 132°52′W	2,400	Red clay	magnetic spherules
327	36°48′S 42°45′W	2,900	Red clay	magnetic spherules
333	35°36′S 21°12′W	2,025	Glob. ooze	magnetic particles
338	21°15′S 14° 2′W	1,990	Glob. ooze	magnetic spherules and bronzite spherules
346	2°42′S 14°41′W	2,350	Glob. ooze	magnetic spherules
347	0°15′S 14°25′W	2,250	Glob. ooze	magnetic spherules
353	26°21′N 33°37′W	2,965	Red clay	magnetic particles

From the tables in the report of the *Challenger* Expedition the present Table 2 has been compiled showing the stations where cosmic material was observed. Some of the stations only register " magnetic particles " and are therefore not considered fully reliable from the point of view of our problems, but they are inserted here in spite of this fact because it may be a question of terminology only. Apart from these stations other 14 stations are left yielding particles of the special character described as cosmic bodies by MURRAY and RENARD.

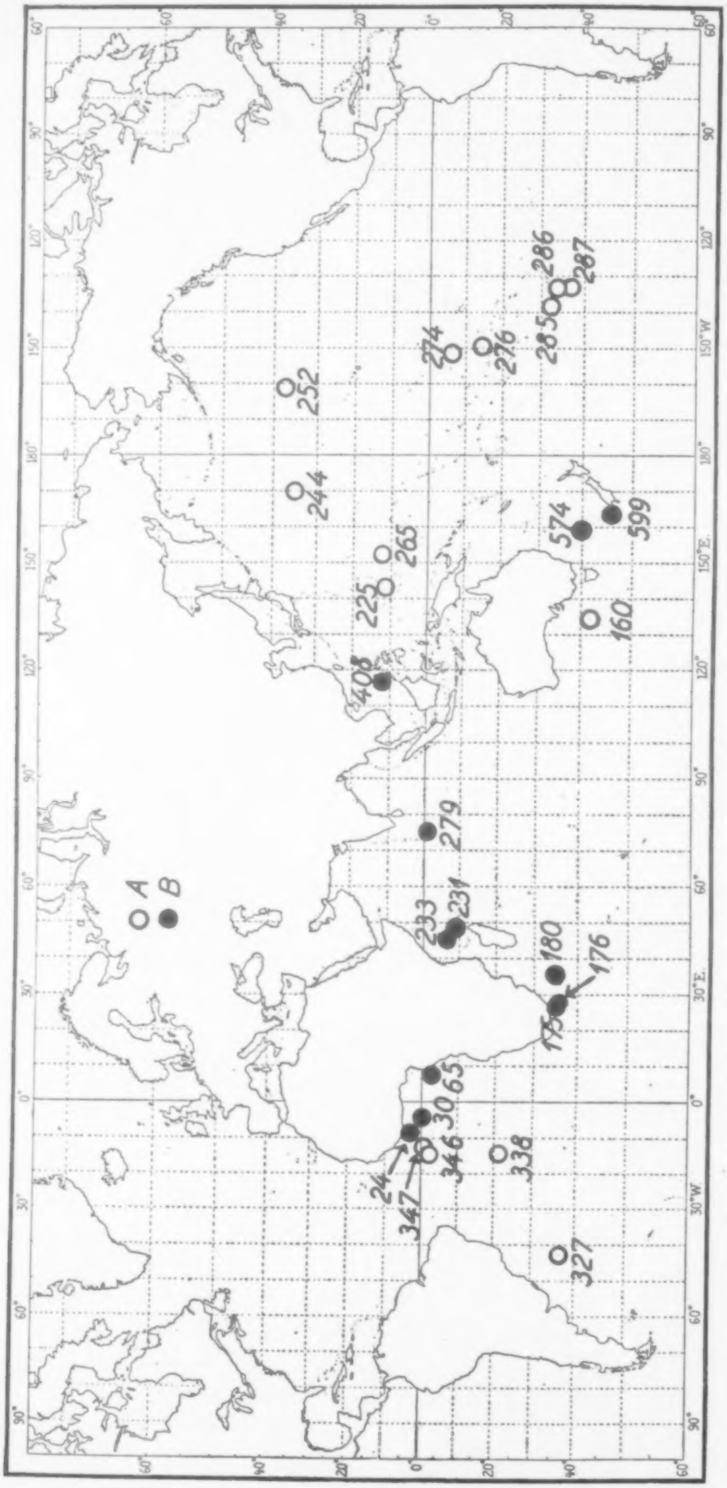
DISCUSSION OF THE MATERIAL

Twelve stations scattered over nearly half the globe yielding little more than 1·5 gr of material do not seem to represent anything out of the ordinary statistically. It must, however, be borne in mind that this material, brought home by the *Galathea* Expedition, represents more than 300 peculiar particles.

More than 100 small shining, black spherules of nearly identical appearance are found in 9 different places; about 100 dull, greyish-brown spherules all very much alike were found in material from 9 stations; at least 50 reniform or scoriaceous particles all of the same general character were observed in samples from 11 stations; and 5 stations yielded metallic particles of a very special composition, this partly appears from the microscopic examinations but is also evident from the fact that the particles were not really rusty as were the nail and the other artificial products found in some of the samples.

When comparing the material from the two expeditions it is obvious that there are certain discrepancies in the descriptions, but on the other hand it is evident that the particles from both expeditions have so many features in common that there is hardly any reason to differentiate between them.

Taking into account the material from the *Challenger* Expedition at least other 14



Map. (*B*) Positions of the stations of the *Galathea* Expedition 1950-52 and (*A*) the *Challenger* Expedition 1872-76.

localities may be added, so the number of stations rises to 26; the number of particles is, of course, greatly increased. The map shows the positions of those places from which the odd particles have been obtained by the *Challenger* Expedition and the *Galathea* Expedition.

With the material from the old expedition a special contribution to our suggestions about the origin of the particles has been given because it eliminates some sources of " modern origin "; Material from weldings, modern battleships, etc.

SIMILAR MATERIAL FROM THE SWEDISH DEEP SEA EXPEDITION

Particles very much like those found by the *Galathea* Expedition have been found by the Swedish Deep-Sea Expedition 1947-48 in the deep sea sediment cores. This information was given by Professor O. Mellis, Stockholm, who also showed one of the authors (H.P.) some of the particles which he and T. Laevastu have examined. A few of these particles have diameters of about 0·1 mm but most of them are only some hundredths of a millimetre in diameter. The particles which were shown were much like the dull greyish-brown particles of the *Galathea* material, and some of the sectioned and polished particles of the Swedish material were clearly silicate particles with minute crystallites of magnetite included, i.e. of the same microscopic character as the dull spherules.

It was of great interest to learn about these observations and especially to have the opportunity to see some of the particles. The occurrence of these particles deep in the ocean-sediments also excludes an artificial origin at least as regards the silicate particles with magnetite inclusions, the rate of sedimentation involving a rather high age of the particles found in the cores.

We seize the opportunity to express our cordial thanks to Professor Mellis for his valuable information. (H.P.)

EXPERIMENTALLY PRODUCED PARTICLES

The experiment was carried out in the laboratories of the Department of Metallurgy at the Technical University of Denmark. The aim was to synthesize drops of the same structure and composition as were found in the material from stations 24 and 30 of the *Galathea* Expedition, namely the metallic spheres which seemed to represent a primary iron-nickel solid solution with interdendritic eutectic carbide structure.

The Nickel-Carbon system

Ni_3C is like Fe_3C meta-stable, and in (Goldschmidt 1948) the following diagram for the binary system is given: The heat of formation of Ni_3C is + 9 Kcal/mol, whereas the corresponding value for Fe_3C is + 2·5 Kcal/mol; Ni_3C is thus less stable than Fe_3C. Ni_3C is said to be relatively stable over 1,600°C and below 300°C. A drastic quenching of a carbon-containing nickel melt is therefore necessary when it is attempted to produce the carbide.

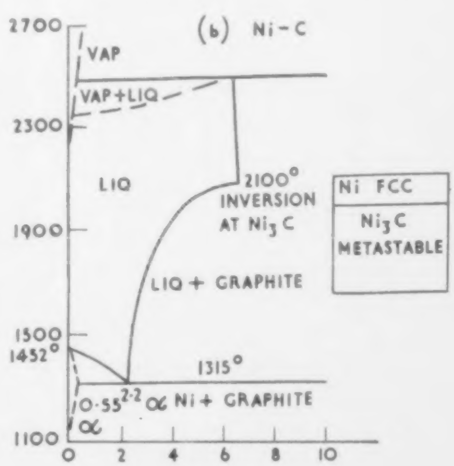


Fig. A.

Nickel-Iron-Carbon system

In (GOLDSCHMIDT 1948) the stability diagram at room temperature is given, and from this it appears that the composition corresponding to that which may be expected for the particle from station 30 (some two per cent of carbon, 8-30 per cent of nickel and the rest iron) includes the structural components graphite + austenite + possibly ferrite.

Rapid cooling may result in (1) carbon being precipitated as a mixture of Ni_3C and Fe_3C that are miscible without forming a ternary carbide, (2) the transformation γ-α being suppressed due to the well-known hysteresis in the presence of nickel.

Thus we may expect a structure in these alloys, when rapidly cooled, consisting of austenite with interdendritic carbide, some of which may be broken up into metal and graphite.

The Experiment

About 10 gr of carbonyl nickel and 10 gr of white cast iron (containing 4·4% C, 0·2% Si and the rest Fe) were melted together in a crucible of graphite by means of an oxy-acetylene torch which was kept reducing in order to prevent oxidizing of the melt. After being melted and stirred with a wire of pure iron the molten metal at a temperature of 1,500 C was poured into a container with water of room temperature from a height of about 1 metre.

At the first run the temperature was a little too low and the material did not get time enough for a total dissolution of the Ni in the melt. Therefore another run was made according to the above conditions.

Results

In both runs spheres were formed. In the first run some spheres of a rather dark grey black colour were seen. In one of them was a distinct cupule, similar to that found in many of the *Galathea* particles. Another of the dark artificial beads which was easily broken turned out to consist totally of magnetite forming a shell only, so that the resemblance to several of the odd particles from the ocean bottom seems fairly marked.

Two of the spheres from the second run were polished and studied microscopically, one had a diameter of 2 and the other of 3 mm.

In both a dendritic structure was formed similar to that of the spherule from stations 30 and 24. The interdendritic mass was anisotropic just as in the *Galathea* particles. By etching the particles with diluted aqua regia the structure seen in Fig. 13(*b*) was developed.

The structure of both specimens consists of well developed dendrites of a solid solution of nickel and iron. The interdendritic space is filled up with a eutectic mixture of carbides and solid solutions.

In some areas graphite is observed as small black particles closely associated with the carbide, it is assumed that the graphite has originated from the decomposition of Ni_3C, thus the remaining carbide is enriched in iron-carbide.

On comparing the smallest of the artificial particles with the particle from station 30 it seems beyond doubt that the structure as well as the components are very similar, if not actually identical, In the specimen from station 30 one of the eutectic components has a greater tendency to crystallize on the primary crystals. In the artificial specimen this is not the case, here the eutectic structure is of a more normal appearance with the two components in intimate mixture.

The experiment demonstrates that particles like those found at stations 24 and 30 may be formed by heating the substance to fairly high temperatures followed by quenching from the liquid state. Ni_3C is obtainable in this way only. (E.L.)

SUGGESTIONS OF ORIGIN OF THE PARTICLES

Conditions as special as mentioned for the formation of the nickel-carbide do not seem to be obtainable in ordinary stokes or the like, and they are surely not to be expected in any terrestrial occurrence either. Therefore the assumption of a cosmic origin for the two particles from stations 24 to 30 seems to yield the most reasonable explanation of their formation.

The black magnetite-spheres may be formed in the same way as was seen in the experiment, and they may be either artificial or cosmic products as they have never been observed in terrestrial formations.

The magnetite-bearing silicate spheres can surely not be artificial products as they were found in strata many hundred years old by the Swedish expedition, and as they do not match with known terrestrial occurrences the only possibility left seems to be the theory of a cosmic origin.

The phosphorous particle from station 279 is more in agreement with cosmic material than with anything else.

STONY METEORITES AS MATERIAL OF COMPARISON

As the cosmic origin of all the odd particles thus seems probable it would be of interest to compare them with meteorites. Certain observations made in the course of an examination of two Danish meteorites seem to be of some importance. Both of them are stony meteorites: the one is the Mern Meteorite fallen 1878 and the other the Århus Meteorite fallen 1951. A more detailed study of them will later be published, but here some observations concerning the external parts will be given.

Under the microscope the crust of both meteorites is seen to consist of a semi-opaque silicate mass with minute crystals of magnetite, and the zone is further characterized by the presence of a great number of cavities. The magnetite crystals observed are of the same shape as found in the dull greyish-brown spherules. Here and there in the largest crystals zonal development was noticed, a darker inner zone and a lighter magnetite-coloured outer zone as in the dull spherules, and also in this case the boundaries between the zones were diffused. Fig. 14 shows an area of the crust of the Mern Meteorite. The thickness of the peripheral zone was up to half a millimetre.

Next to this zone comes a zone characterized by the presence of lots of veins of sulphidic material. Both grains of sulphides and metal occur in this zone, but whereas the sulphidic grains often are intimately associated with the veins the metallic grains seems to have been little affected by the processes which caused the formation of the zone. The most conspicuous feature, however, was the finding of a nice example of pentlandite exsolution lamellae in some of the troilite grains in the vein zone. This has not been found in the inner parts of the two meteorites where, by the way, it was not to be expected either, as it is supposed to have been formed by the processes which otherwise formed the zone.

In the Mern Meteorite olivine crystals were fairly often found as inclusions in the metallic phases, as is also described in literature on other meteorites.

SUGGESTIONS OF MODE OF FORMATION OF THE PARTICLES

A comparison of the particles with iron meteorites, as was made by MURRAY and RENARD, may be of great interest, but as a rather large number of the particles

contain silicates, the stony meteorites may be of great importance too. The brief study of the two Danish meteorites suggests that most problems connected with the odd particles may be explained if the stony meteorites are supposed to be the source of the material, and exactly the source in the sense of MURRAY and RENARD.

All the material found in the odd particles may also be found in the stony meteorites, and the fate of the meteorites from the time they enter the atmosphere seems to give us exactly the conditions required for the formation of the particular spheres from stations 24 and 30 containing nickelcarbide, which are also needed for the formation of the other particles.

The outer crust of the meteorites is, on their passage through the atmosphere, heated to pretty high temperatures. The Danish meteorites mentioned show at least 1,000°C judging from the presence of sulphide veins. In the magnetite zone, the external crust of the meteorite, the temperature must have been higher, and we may safely assume that part of the meteorite surface has disappeared during the flight through the air. This part of the meteorite has melted and as a result of the high velocity and the air resistance it was blown off and formed the tail of the meteor. Thus this consisted of droplets of melted material of the elements present in the cosmic body. Droplets of metal and/or sulphide may have oxydized and formed the black shining spherules; where silicates were at hand the dull greyish-brown spherules were formed. The layers nearer to the crust still to be found on the meteorite may have supplied material to the larger reniform and slag-like particles.

The size of the odd particles may perhaps be determined by the size of the corresponding material in the meteors. It is therefore interesting to note that from the study of Danish meteorites it appeared that the grains of metal and sulphide were generally about some tenths of a millimetre, a few of them being up to one mm across, or a little more. The silicate-areas free from sulphides and metallic grains may be some mm in diameter thus the silicate bearing particles may attain greater dimensions than the other particles.

The single droplets forming the tail of the cosmic body are exposed to the very low temperatures of the upper layers of the atmosphere and therefore very rapidly cooled; and thus the formation of such components as Ni_3C may be possible.

In the description of the metallic particles from the *Galathea* material it was mentioned that the graphite lamellae seemed more frequent in the peripheral parts of the particles. This may indicate that the carbon was absorbed from the atmosphere, but it is of course difficult to know. Carbon is a well known element in meteorites, and the carbon in the particles mentioned may of course be of the same origin as the other elements present.

The pentlandite-like mineral found in one of the particles from station 279 is interesting, because this mineral was observed as a constituent in the crust of the meteorites mentioned.

The minute grains of metallic matter found in some of the silicate particles from the ocean bottom seem in keeping with the point of view here evolved, and so does the occurrence of a rhombic silicate found in the metallic particles from station 279; it was quite similar to the olivine crystals observed in the Mern Meteorite.

The osbornite-like mineral found in the same particle from station 279 is rather extraordinary. The mineral osbornite has as yet only been found in the Bustee Meteorite by STORY MASKELYNE (1870).

ROUGH ESTIMATES OF THE AMOUNT OF THIS MATERIAL FALLING ON THE EARTH

This explanation of the origin of the odd particles, adopted from MURRAY and RENARD, appears to be rather unique, but it seems in perfect conformity with all observed data. Consequently, this material and cosmic dust are two different things. It would therefore be interesting to try and form an idea of the amount of this material the earth receives per year. It is of course only possible to get a very rough estimate of the order of magnitude but it may nevertheless be of a certain value.

The estimated length of haul as stated in Table 1 for each station gives a total length of sampling of about 45·000 m. As the magnetic rake had a breadth of 1 m, the total area covered is not more than 45·000 sq. m. All samples together contain at least 300 particles and thus we get one particle per 150 sq. m. The rake is supposed to work in the upper 1 cm layer only. If the sedimentation is put as high as 1 cm in 500 years we arrive at 7×10^9 as the number of particles falling on the whole surface of the earth. The weight of these particles corresponding to the estimated percentages of cosmic matter in the samples would be about 30 ts.

This number is extremely low compared with what is assumed to be the amount of cosmic material falling on the earth. The above computations are rather uncertain but we have to multiply with such high figures as 10^4-10^6 in order to reach the figures assumed by various authors and this would not be in keeping with the *Galathea* material. The computations may therefore be interpreted as favouring the idea of the particles originating only from the tail of the larger cosmic bodies which enter the atmosphere of the earth.

Owing to their very special character and considering their peculiar origin it may be useful for the present to distinguish these particles from other cosmic bodies by giving them the name of caudaites.

ACKNOWLEDGMENTS

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The examinations were greatly dependent on the preparation-process and it was therefore of great importance that the Kryolitselskabet Øresund A/S generously allowed us the use of laboratories and equipment for these out of the way examinations. For this we render our sincere thanks.

We further have to thank the Director of the Mineralogical Museum of the University, Professor ARNE NOE-NYGAARD, Ph.D., most heartily for the encouraging interest he at all times has taken in our work.

The chemical determinations have been undertaken by Mr. A. H. NIELSEN, chemist at the Kryolitselskabet Øresund A/S, for this and for his never failing interest in the problems we want to bring our best thanks.

Copenhagen

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LETTERS TO THE EDITORS

A plea for Oceanology

(*Received 21st January*, 1955)

IN putting forward his : " A plea for Oceanology " (this journal——issue of January, 1955) Commander HALL is rather flogging a dead horse.

The use of the words " Oceanology " and " Oceanologist " was well and truly pondered in days past. Today they are little used save in Russia. In the Scandinavian countries particularly – but in others as well – the people who, in Britain, are known as oceanographers, go under the label of hydrographers.

That well-established and fitting label is especially current in Dr. BRUUN's country for the practitioners of Physical Oceanography, but, because the word " Hydrographer " had come to have a special meaning in Britain and the U.S.A., attempts were made to avoid other use of it in those two countries. There is very much about it all in the pages of the Monaco Hydrographic Review around 1934 and earlier.

Choice of the words " Hydrology " and " Hydrologist " by the Discovery Committee was not a very happy one because of their long-established different meanings. Whatever the dictionaries have to say about these latter, it is officially laid down within the International Union of Geodesy and Geophysics that the concern of " Hydrology " is with Potamology, Limnology, Snow and Glaciers, and Subterranean Waters.

Though there is a disposition nowadays to talk of marine physics as distinct from marine biology, the terms " Oceanographer " and " Oceanography " are so solidly fixed by long usage as to persist – and they are suitable. If we go back to word meanings, " Oceanology " connoting discourse about the ocean seems nothing preferable to " Oceanography " signifying descriptive writings about the oceans. " Oceanognosy " would be a very ugly word to propose.

If " Oceanography " be the glaring misnomer which Commander HALL contends, what then is " Hydrography " with the connotations it carries as a label for Commander HALL's profession so little concerned with water (apart from depth) and so much occupied with coasts, astronomy, navigation, position-fixing, etc.

Whereas Chambers defines hydrography as having most of the meaning current in the British Admiralty, the Concise Oxford Dictionary does not.

Does Commander HALL really regard hydrography as a particular facet of hydrology as acceptably defined above, and biography as a subdivision of biology ? If so, accepted meanings go by the board. There is no easy escape from nomenclature problems to which considerable thought has frequently been given. It would be exciting to be present at a meeting of geographers who had just been told that their science is a particular facet of geology.

J. N. CARRUTHERS

National Institute of Oceanography, England.

Le Bathyscaphe F.N.R.S.3
Au Service de l'Exploration des Grandes Profondeurs

LA PRESSE a beaucoup parlé depuis un an des bathyscaphes et de leurs plongées à grande profondeur. Mais il est à craindre que l'intérêt qu'elle a marqué à des " records " momentanés et sans valeur n'ait masqué les véritables buts poursuivis.

Le bathyscaphe F.N.R.S.3 a été construit par la Marine Francaise, avec l'aide financière du Centre National de la Recherche Scientifique (francais) et du Fonds National de la Recherche Scientifique (belge) en vue de l'exploration de la Mer, jusqu'à une profondeur maxima de 4.000 mètres; ce dernier chiffre n'a pas été choisi au hasard. Aucun engin autonome n'avait auparavant

descendu ses passagers plus bas que 250 mètres environ: le saut de 250 à 10.800 mètres paraissait énorme et la prudence conseillait de ne le tenter que par étapes. On se borna donc pour débuter à une valeur intermédiare, très voisine de " la profondeur moyenne des mers."

C'est ainsi que la période des essais se termina par une plongée à 4.050 mètres, effectuée le 15 Février 1954 à 130 milles marins au sud-ouest de Dakar. Cette plongée prouva, en même temps que la grande sécurité de l'appareil, ses possibilités d'évolution au sein de l'océan et de séjour sur le fond.

Conformément au programme initial, la Marine avait donc mis au point un laboratoire sous-marin; elle en avait construit les murs; il restait à l'utiliser et à l'équiper. La complexité des problèmes à étudier et les nécessités matérielles d'entretien et de mise en oeuvre du F.N.R.S.3 ne pouvaient qu'encourager le C.N.R.S. et la Marine Nationale à poursuivre una collaboration qui avait déjà donné de si heureux résultats: le 3 Mai 1954 une convention passée entre ces deux organismes réglait les modalités d'emploi, en vue de recherches scientifiques, de l'engin qui demeurait propriété de la Marine. En échange d'une contribution financière, le C.N.R.S. avait le droit de faire effectuer dans l'année 15 plongées à des observateurs de son choix; qu'il me soit permis de rappeler ici que la sphèer " nacelle " ne peut contenir que deux personnes et que la présence du pilote indispensable ne permet donc d'emmener qu'un spécialiste chaque fois.

Quelques semaines avant la signature de cette convention, le C.N.R.S. avait déjà nommé une Commission chargée d'établir un programme de travaux. Placé sous la haute présidence de Monsieur le Professeur Fage, Membre de l'Institut; ce Comité de direction réunit un certain nombre de personnalités scientifiques représentant toutes les disciplines susceptibles de tirer un profit de l'exploration des mers en profondeur: biologie, physique, hydrographie, océanographie, géologie, et bien d'autres. Dès sa constitution, le Ier Avril 1954, cette Commission autorisait Monsieur le Professeur Monod, Directeur de l'Institut Francais d'Afrique Noire, à profiter du sejour du bathyscaphe à Dakar pour effectuer deux plongées en Atlantique. Depuis le retour en France plusieurs plongées ont été effectuées avec Monsieur Peres, Directeur de la Station Marine d'Endoume, à Marseille, et son assistant Monsieur Picard, outre les expériences réalisées pour le compte de la Marine elle-même.

Il ne m'appartient pas de me substituer à ces spécialistes qui feront part, eux-mêmes, du résultat de leurs observations. Mais il m'est permis d'établir un bilan sommaire des plongées que j'ai effectuées et d'envisager un premier avenir.

Dès le début de nos essais, tant est passionnant le spectacle à travers le hublot, Willm et moi nous sommes efforcés de décrire ce que nous avions vu.

Un des phénomènes les plus immédiatement perceptibles dès l'arrivée sur le fond est la découverte de courants parfois fort importants; certes il est difficile de s'aventurer dans ce domaine sans avoir effectué des mesures précises. Mais il est des visions qui ne trompent pas et, dans ce domaine, elles sont nombreuses. Qu'on imagine le F.N.R.S.3 reposant sur le fond par le chassis support de la sphère; son immobilité est alors totale. On voit aussitôt défiler dans le faisceau des projecteurs les animalcules qui constituent le plancton; cette matérialisation du courant peut même être améliorée par un léger laché de lest qui soulève en tombant un petit nuage de vase dont il suffit d'observer la disparition. Les animaux eux-mêmes nous aident parfois, témoins ces *Halosaurus* vus au large de Dakar et qui se tenaient parfaitement fixes par rapport au fond, face au courant, en faisant onduler leur longue queue témoignant d'un ancestral entrainement à cette attitude. Mieux encore, au mois de Janvier 1954 et à 750 mètres de profondeur, toujours au large de Dakar, Willm et moi avons vu notre bathyscaphe littéralement emporté par le courant, la trainee dés 6 à 7 mètres de chaine du guide-rope qui reposaient sur le fond était nettement insuffisante pour nous arrêter. Je dois ajouter, à ce sujet, que lors des plongées effectuées en Méditerranée, au cours de cet été, je n'ai guère rencontré de courants. Il y a néanmoins là un élément extrêmement important à étudier, puisqu'il semble en opposition avec ce qui était généralement admis dans ce domaine. C'est une étude qui sera relativement facile à mener puisqu'il suffit d'adapter quelques courantomètres au bathyscaphe et que le compas magnétique fonctionne depuis plus d'un an; mais c'est une étude qui sera longue par suite de la nécessité d'effectuer des séries de plongées au même endroit et de mesurer les courants pendant des intervalles assez longs et à différentes époques de l'année.

Une autre vision qui a frappé tous les passagers du bathyscaphe lors de la lente descente depuis la surface jusqu'aux plus grands fonds atteints a été celle du grouillement planctonique. Si l'on rapproche la densité de ces petits organismes observée, à l'oeil nu, à travers le hublot, aux quelques échantillons ramenés à grand peine dans un des actuels filets dits " à plancton," on est obligé de

reconnaître la médiocrité des appareils utilisés. Le F.N.R.S.3 doit permettre une étude plus facile et une numération à toutes profondeurs. L'oeil est trop imparfait pour qu'on puisse, dès maintenant, avancer une précision quelconque; il nous dit cependent que la densité paraît sensiblement constante de 150 à 200 mètres (profondeur à laquelle le faisceau des projecteurs commence à se matérialiser dans l'eau sombre) jusqu'au voisinage immédiat du fond avec une légère diminution dans les deux ou trois derniers mètres.

Bien entendu les ichtyologues sont les premiers à trouver des satisfactions au cours d'un séjour sur le fond; de nombreux animaux se présentent d'eux-mêmes à l'observation et rien n'est plus simple qu'étudier leur comportement dans leur élément, au milieu de leur domaine familier et de les photographier. Déjà le crabe " géant " a troublé le Professeur MONOD, à Dakar, et la photographie d'un " poisson " que j'ai observé pendant plusieurs heures, posé à 2.300 mètres de profondeur sur trois longues " antennes " prolongeant les nageoires pelviennes et la queue a été une révélation: le Professeur BERTIN, du Museum National d'Histoire Naturelle, l'a identifié comme étant un *Benthosaurus* dont les longs filaments avaient été considérés jusqu'à présent comme purement tactiles. Il importe désormais de conjuger la prise de vue avec la capture des animaux qui, seule, donnera une identification rigoureuse: déjà nous avons essayé les moyens simples, lignes appatées et nasses. Nous n'avons jusqu'à présent obtenu aucun succès, mais le comportement des animaux, vus à travers le hublot, en face de nos appats, nous a donné de bons renseignements: les squales ont dévoré les appats; s'ils n'ont pas été accrochés, c'est à cause de la mauvaise forme des hamecons utilisés. Les *Haloporphyrus* se sont montrés fort attirés par la nourriture que nous leur apportions, mais les hamecons prévus pour des squales étaient beaucoup trop gros pour des animaux de petite taille. De grosses crevettes de 10 à 15 centimètres sont restées pendant 4 heures, à 2.300 mètres, accrochées aux cadavres de limandes prouvant que la nourriture apportée dans ces grands fonds était loin d'être sans intérêt. Il nous est donc permis d'espérer des captures dans un avenir proche. Par contre, pour les *Benthosaurus*, posés sur leurs filaments, dans une attitude de statue, il convient d'envisager des appareils nouveaux qui iront " chercher " l'animal et le retiendront captif.

Géologiquement aussi le bathscaphe doit rendre de grands services; les résultats en sont sans doute moins immédiats et il est absolument indispensable d'attendre un matériel spécial actuellement à l'étude. La seule observation à travers le hublot ne nous a montré jusqu'à présent que de la vase, à l'exception d'une fois. Ce jour là, je plongeais à 2.300 mètres, à une dizaine de milles au sud du Cap Sicié, théoriquement dans la grande plaine Méditerranéenne, nettement au large de la zone montagneuse et découpée qui relie le plateau continental aux grands fonds. Contrairement aux plongées précédentes effectuées dans la même région, je me suis posé sur un fond rocheux, pratiquement sans vase, avec des falaises verticales d'une vingtaine de mètres de haut. Par contre, toutes les plongées effectuées dans le canyon de Cépet lui-même ne nous ont jamais montré que de la vase très légère, déposée sur des parois aux pentes très fortement accusées, sans aucune roche visible. Le travail de prélèvement des sédiments sera sans doute très intéressant car l'opérateur pourra juger, grace au hublot, de la facon exacte dont travaillent les appareils et même choisir son emplacement.

Ainsi, tout un programme de travail est, d'ores et déjà, élaboré; il se modifiera de lui-même et se complètera à mesure que les spécialistes plongeront et que le matériel de recherche se perfectionnera. C'est une nouvelle technique d'étude de la mer que est en route: tous les éléments de cette étude, Comité de direction, spécialistes et bathyscaphe sont dès maintenant réunis; le matériel spécial est à l'étude ou en construction. Il convient d'attendre, avec patience, les prochains résultats.

Capitaine de Corvette HOUOT
Commandant du Bathyscaphe (*Toulon*)

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Book Review

Climatic change: evidence, causes, effects. Papers by twenty-two authors, edited by HARLOW SHAPLEY. *Harvard University Press, Cambridge, Mass.* (*London* : *Geoffrey Cumberlege, O.U.P.*). 1953. Pp. xii + 318; maps, diagrams, illustrations; references; no index. $6.00 (48s.)

OCEANOGRAPHERS who concern themselves with the depths cannot but be aware of the promise afforded by recent developments in core-sampling, and especially by the many cores obtained by the *Albatross* expedition, 1947-49. With a little imagination it is not difficult to conjure up the vision of queues of eager climatological investigators begging for a sign whenever the deep-sea scientist emerges from long hours in the laboratory devoted to the patient scrutiny of the results of half a million years of sedimentation so revealed. The number and character of the glaciations; the dating of the Bölling oscillation now that the Alleröd is becoming familiar; the amplitude of such oscillations, and even the climatic vicissitudes within recorded history are all demanded, or at least devoutly hoped for, by numerous workers in other fields.

The study of climatic change has indeed become very active in recent years, and has given rise to discussions or symposia at several international assemblies. Much of the credit for this must be ascribed to the glaciological studies by Dr. HANS AHLMANN and his many colleagues, which have coincided with a period during which a quite appreciable climatic amelioration has developed around the northern Atlantic. Relationships between the surface behaviour of the ocean waters, the spread of sea-ice, and climatic vicissitudes have long been studied, especially in N.W. Europe for obvious reasons. Such investigations have also been stimulated as a result of the recent amelioration, illustrated for example by Dr. JENS SMED's papers from Denmark. It is noteworthy that until recent years, by contrast with Danish work in Greenland waters, little has been done in Hudson Bay or the Canadian Arctic; but such deficiencies are being rapidly overtaken as recent Canadian papers such as those by M. J. DUNBAR and S. ORVIG show. Both the character and the rate of deep-sea sedimentation are likely to be affected by surface vicissitudes, and the interrelationship between variations in the atmosphere circulation and that of the ocean still requires much elucidation.

Deep-sea investigators meanwhile cannot but reciprocate the geologists' interest in their studies, together with that of other scientists wanting knowledge of past climate. Fresh from the perusal of the latest efforts at radio-carbon dating or the counting of foraminifera they may wish to extend their knowledge and learn what is going on in what is, after all, one of the fundamental subjects of geophysical enquiry. They can be commended with confidence to the work under notice. It is an assemblage of papers given at a two-day conference organised by the American Academy of Arts and Sciences in 1952. The collection has been edited by Dr. HARLOW SHAPLEY, who also contributes a lively introduction. Harvard and Yale between them provide fourteen of the contributors. Six of the papers can be described as " astronomical " in content, four are meteorological; several of the rest are concerned with various types of geological and botanical evidence for climatic change, while C. S. COON for example discusses climate and race. Most of the standard questions with which we have been familiar have again been attacked, sometimes from a fresh standpoint. Among the causes of climatic variation, the possibilities of solar corpuscular radiation are considered, described in her paper by BARBARA BELL as the only known source of energy that acts exclusively in high latitudes; H. C. WILLETT provides a compact summary of the ideas he has been developing for several years with regard to variations in the atmospheric circulation; in a discussion of the earth's radiation balance, H. WEXLER raises again the possibilities of volcanic dust. E. S. DEEVEY contributes a long essay on " Paleolimnology " in which technique, method and results will have an obvious interest for oceanographers; J. L. KULP discusses the value of radioisotopes in dating. Among the astronomical contributors VAN WOERKOM and BROUWER provide a recalculation of variations in the earth's orbital elements with results differing somewhat from those of MILANKOVITCH. E. SCHULMAN gives an up-to-date summary of the value of tree rings in the interpretation of past fluctuations in the south-west United States; R. F. FLINT discusses evidence for climatic change provided by glacial geology. J. H. CONOVER provides an interesting short paper illustrating the need for caution in using instrumental meteorological records as evidence of change. From the above eleven contributions – half the total – the diversity and wide interest of the papers is apparent; and the remainder are equally enlivening.

In common with others who pursue geophysical studies, oceanographers must perforce have command of more than one science; and they will accordingly find abundance of stimulating reading in this collection of papers around the theme of climatic change. In the editor's words, the field is one in which physical and biological sciences meet, with much lively mental exercise as a result. There is little direct comment on the more immediate concerns of the oceanographers, beyond a page or two in which WILLETT gives reasons for relegating the oceanic circulation to a position of secondary importance vis-à-vis that of the atmosphere, more particularly in regard to latitudinal heat transport; while elsewhere KULP comments on the PIGGOT-URRY method of determining age of deep-sea sediments. The book is rather to be commended as pleasant background reading for the deep-sea scientist who is already familiar with such earlier works as BROOKS " Climate through the Ages." Most of the papers are supported by abundant references; and printing and production are admirable.

GORDON MANLEY

ANNOUNCEMENT

A Volume of Contributions to Oceanography by colleagues and students of Henry B. Bigelow will be published in his honour as a supplement to Volume 3 of "Deep-Sea Research." It will be presented to him during 1955, in commemoration of the twenty-fifth anniversary of the founding of the Woods Hole Oceanographic Institution, with which Dr. Bigelow has been closely associated as a founder, as the first Director, as President of the Corporation and now as Chairman of the Board of Trustees.

The volume will contain original scientific papers and review articles on the biology, chemistry and physics of the sea. These will reflect Dr. Bigelow's own wide interests in the sea. The following topics have already been submitted :—

A West Indian hydrocoral.
Distribution of the Chaetognatha in relation to the hydrography of the waters south of Cape Hatteras.
Ausbreitung des Mittelmeerwassers im Atlantischen Ozean vor der Strasse von Gibraltar.
Bermudian gorgonians.
Effect of added nutrients to the rate of photosynthesis by plankton.
La teneur en oxygéne de l'eau au contact du fond.
Underwater sounds and orientation of marine animals.
Water replacements and their significance to a fishery.
Accumulation of river water on the continental shelf between Cape Cod and Cape Hatteras.
The feeding of Calanus on cultures grown with radio-active carbon.
Planktonic Foraminifera from the Mediterranean.
Foraminifera in the Gulf of Mexico off the Mississippi delta.
Observations on the distribution of carbon dioxide in the North Pacific.
Intertidal investigations in Loch Sween in relation to fertilization.
The hydrography of the Gulf of Venezuela.
Discussion as to whether fish originated in fresh or salt water.
A fish community over the continental slope.
Interaction between phytoplankton and bacteria in the sea.
Strontium-calcium ratio in carbonate secreting marine organisms.
Larval transport and speciation in marine bottom invertebrates.
Development and metamorphosis of the larva of *Agalma elegans* (Sars) (Siphonophora Physonectae).
" Atlantis " scaphopods.
Marine bacteria : recollections and problems.
The dimension of time in fishery research.
Polarization of light in deep water near Barbados.
Nature of "jelly-fish poison."
Sea salt in the air and rains of Hawaii.

The supplement in honour of Dr. Bigelow will be sent to all regular subscribers to "*Deep-Sea Research*" without extra charge. It may also be purchased separately, at a price to be determined later.

11th *February*, 1955. Mary Sears

Deep-Sea Research, 1955, Vol. 2, pp. 253 to 260. Pergamon Press Ltd., London.

Geologic interpretation of a series of seismic reflection profiles from Bermuda to the continental margins

C. B. OFFICER*

INTRODUCTION

THE GEOLOGIC exploration of oceanic areas has proceeded in several directions. Echo sounders are used to study the morphology of the ocean bottom, cores to study the near surface sediments, and seismic refraction profiles to study the properties of the sub-oceanic crust. A further method is that of seismic reflections. Previous investigations over deep water have dealt with vertical reflection measurements from a single ship, WEIBULL (1947) and HERSEY and EWING (1949). Both demonstrated that sub-bottom horizons do exist, and the latter discuss the various types of reflection records that are obtained over the western Atlantic and the differences in sediment structure that they represent. Here, the results from a series of seismic reflection profiles are discussed.

Such reflection profile investigations have been carried out by J. NAFE and J. EWING at Lamont Geological Observatory from profiles giving a broad aereal coverage and by OFFICER (1955) from profiles designed to give a more detailed examination of the physical properties of the sediment. Both show that the sub-bottom reflections can be followed from one record to the next on a profile and that the seismic velocity structure in the sediments can be determined from such profiles. In general, a velocity gradient of the order of 1 ft./sec. per ft. of depth is measured so that beyond a moderate range the angle of incidence on the bottom is such that the energy is returned from a refraction in the sediment column without a deep reflection. The existence of this velocity gradient in the sediment had been demonstrated previously by HILL (1952). The interest in this paper is with the arrivals from records at closer ranges where sub-bottom reflections are received.

On these seismic reflection profiles over deep water two ships were used. The first ship, R/V *Atlantis*, recorded from a hydrophone near the ocean surface. The second ship, R/V *Caryn*, fired small charges at closely spaced intervals on a prescribed track away from the *Atlantis*. A balloon was tied from a piece of string to each charge so that it would fire two feet below the surface. This procedure eliminated the explosion bubble pulse, and the near surface hydrophone eliminated the sometimes complicating effect of surface reflected energy, recorded on a deeper hydrophone. The information was preserved on magnetic tape to be replayed in the laboratory to a galvanometer camera.

STRUCTURE FROM SEISMIC REFRACTION PROFILES

The several published seismic refraction investigations over the North America Basin allow one to draw a rough geologic section along the line of the reflection profiles (Fig. 3). Under the abyssal plain portion the sediment is 3,000 to 4,000 ft.

* Woods Hole Oceanographic Institution, Contribution No. 743.

thick (EWING, SUTTON, and OFFICER, 1954). Under the Bermuda rise southeast of Bermuda the sediment is 1,000 ft. thick and is underlain by a layer of volcanics, and possibly consolidated sediment, varying in thickness from 5,000 to 10,000 ft. (OFFICER, EWING, and WUENSCHEL, 1952). It is inferred that a similar structure is present under the western portion of the Bermuda rise along the line of the reflection profiles. Investigations over the continental rise from Nova Scotia to Georges Bank show an extensive sediment of geosynclinal proportions with a maximum thickness of upward of 15,000 ft. (OFFICER and EWING, 1954). These sediment layers under the continental rise are continuous with those under the continental shelf and Atlantic coastal plain. Wells over the Atlantic coastal plain determine the age of the boundary between the two sediments, shown in Fig. 3, to be of Upper Cretaceous age such that the lower sediment is primarily Lower Cretaceous and possibly Jurassic and the upper layer Upper Cretaceous and Tertiary (EWING, WORZEL, STEENLAND, and PRESS, 1950) ; this age is again checked by samples dredged from the sides of the canyons which incise the continental slope (STETSON, 1949). The basement beneath these sediment layers, from Nova Scotia to New England, is metamorphosed rock of Palezoic and pre-Cambrian ages. The seismic velocities that are measured over the continental shelf for the basement are characteristic of metamorphics ; however, as one progress out over the continental rise there is a significant decrease in the basement velocity down to values which are more characteristic of lithified sediments. It is interpreted that this decrease in basement velocity represents decreasing metamorphism away from the main orogenic belt and that the basement under the continental rise is the now lithified sediment deposited seaward from sources on the continental shelf during the time when large thickness of sediment were being deposited landward to the Appalachian geosyncline. This basement thins and pinches out under the continental rise and is not present under the ocean basin areas. Here, the sediment is underlain by the simatic crust with seismic velocities characteristic of basic to ultrabasic rocks. The Mohorovicic discontinuity, which is at a depth of around 130,000 ft. (40 km.) below sea level under eastern North America, is at a depth of 30,000 ft. (10 km.) under the ocean basin areas.

SEISMIC REFLECTION PROFILES

The locations of the seismic reflection profiles are shown in Fig. 1. Profile 6 is over the Bermuda rise, 5 and 8 over the abyssal plain, 4 at the beginning of the continental rise, and 3 further up the continental rise. A sequence of records from profiles 3, 4, 5, and 6 illustrate the differences in the sediment structure between the areas, (Fig. 2). The subbottom reflections, where observed on each set, can be followed from one record to the next until they merge into the sub-bottom refraction arrival. On profile 6 a strong sub-bottom reflection is observed at a depth of 800 ft. below the bottom plus a strong multiple reflection from the same horizon. This depth correlates with the top of the volcanics from the seismic refraction profiles. On profile 5 a well defined although not quite as strong, reflection is observed at a depth of 1,000 ft. and a second reflection from a depth of 2,800 ft. The deeper reflection is near the bottom of the sediment column as measured from the refraction profiles. Profile 8, which has been discussed in a previous paper (OFFICER, 1955), illustrates the same type of records and measures a similar structure with the two reflectors at 1,200 and 3,400 ft. and in addition a weak multiple of the 1,200 ft. horizon.

is observed. On profile 4 the lower reflector at 2,600 ft. is observed. An upper reflector can be followed for a few records. On profile 3 a deep reflection or possibly deep refraction is observed at range, but the correlation back toward zero range cannot be followed.

These profiles present a consistent picture. The lower horizon of profiles 4, 5, and 8 is near the bottom of the sediment column, probably not the actual contact with the underlying simatic crust but a consolidated sediment zone above this contact. The upper reflector at a depth of around 1,000 ft. is the top of the volcanics under the Bermuda rise. Proceeding away from the Bermuda rise, this horizon is present on profiles 5 and 8, is questionable on 4, and is not present on 3. It is interpreted that the volcanics of the Bermuda rise extend out over the abyssal plain disappearing near the continental rise (Fig. 4). That the volcanic layer under the abyssal plain is thin, of the order of a few hundred feet, is known from the fact that it is not observed on the seismic refraction profiles. It is inferred that at the time of the volcanic activity associated with the building of the Bermuda islands and the Bermuda rise, some of the lava flows, perhaps from fissures on the outer portion of the rise, extended out over the abyssal plain.

The volcanic layer allows an age to be given to a portion of the sediment column under the abyssal plain. A boring on Bermuda (PIRSSON, 1914) reaches the volcanic platform; miocene and eocene foraminifera are found in the sediment immediately above the volcanics. PIRSSON gives the age of the volcanism as Triassic from the last period along the east coast of North America ; however, it may be later and contemporaneous with the volcanism of the Caribbean island arc. Either gives a compressed age scale for the sediment column under the abyssal plain and indicates that the upper third, at least, is Cretaceous or younger. This age agrees with that which might be given from an extrapolation of the known age for the intermediate horizon in the sediment under the continental shelf.

That there is not a uniform age scale through the deep ocean sediment column argues for the premise that, in a geological sense, the abyssal plain areas are not static, that there has not been a uniform increase in sediment with time. Rather there has been a more rapid increase in sedimentation associated with the Atlantic coastal plain. It might be reasoned further that the compressed age scale argues for a previous emergence of the ocean basins; however the author finds this incompatible with the evidence from the measured geologic structure under the oceanic and continental areas. It seems more reasonable to assume that such agencies as mid-ocean canyons (EWING *et al*, 1953) which today transport sediment from one abyssal plain to the next lowest and so on operated in the past in the same manner.

ACKNOWLEDGMENTS

The author wishes to express his thanks to Dr. J. B. HERSEY and Mr. H. R. JOHNSON for valuable discussions during this investigation and to those who took part in the work at sea and the analysis in the laboratory. This work was done under the sponsorship of contract NObsr-43270 with the Bureau of Ships, U.S. Navy.

Woods Hole Oceanographic Institution.

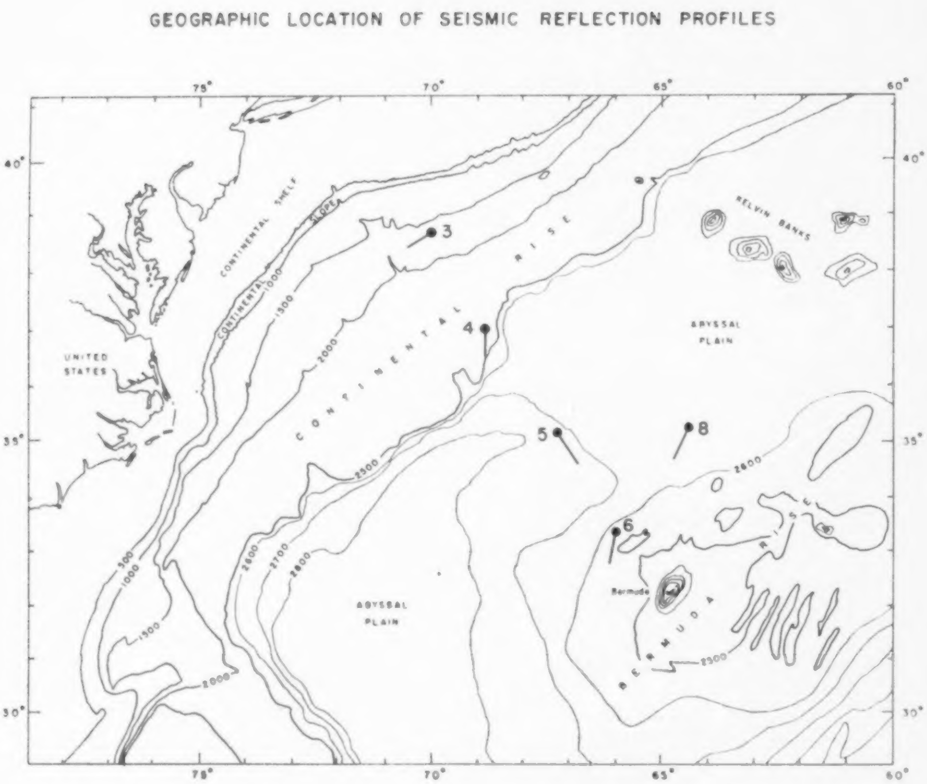
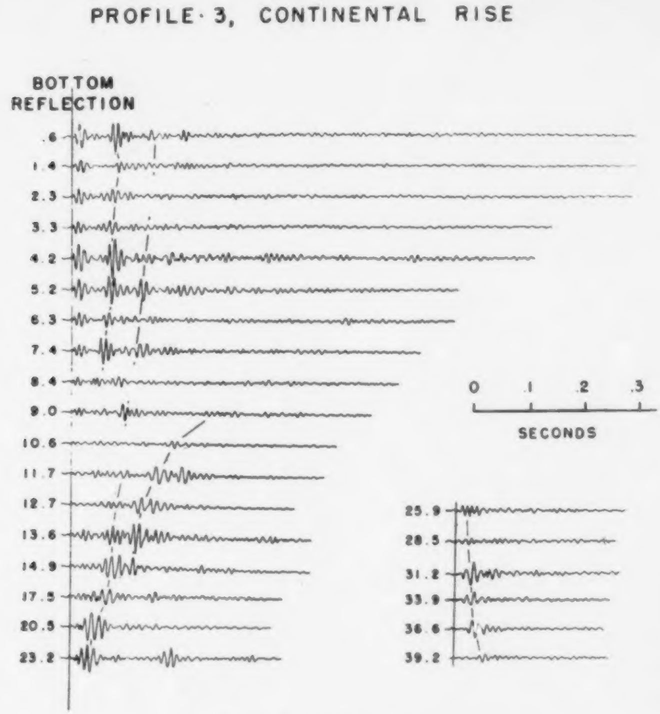
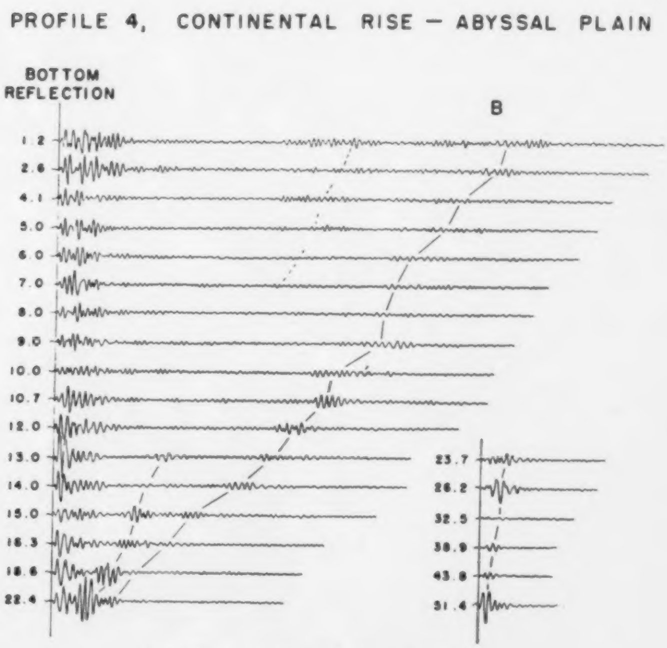


Fig. 1. Geographic location of seismic reflection profiles.

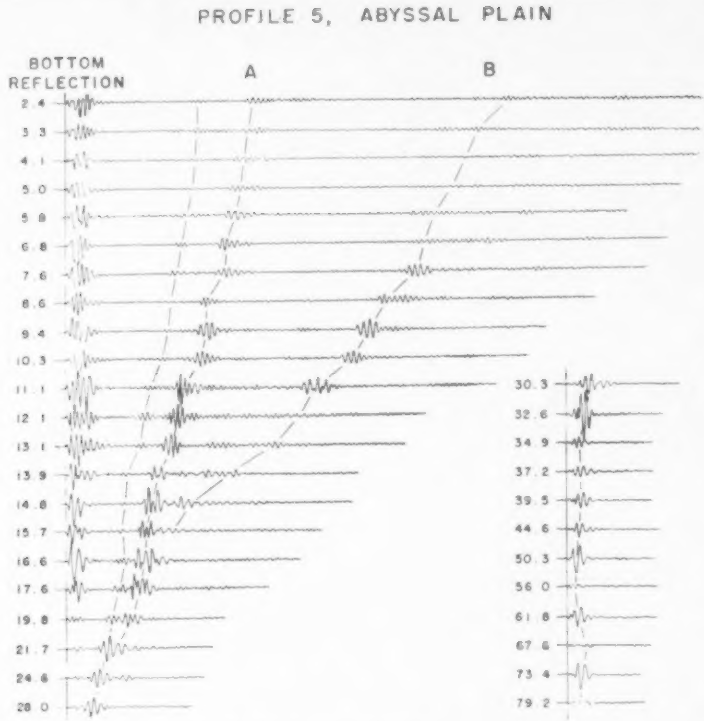


Profile 3, continental rise.

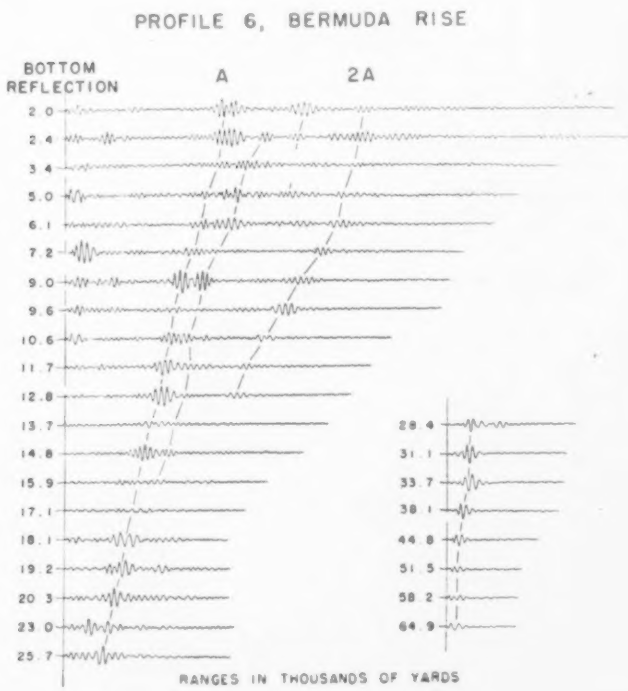


Profile 4, continental rise – abyssal.

Fig. 2.



Profile 5, abyssal plain.



Profile 6, Bermuda rise.

Fig. 2.

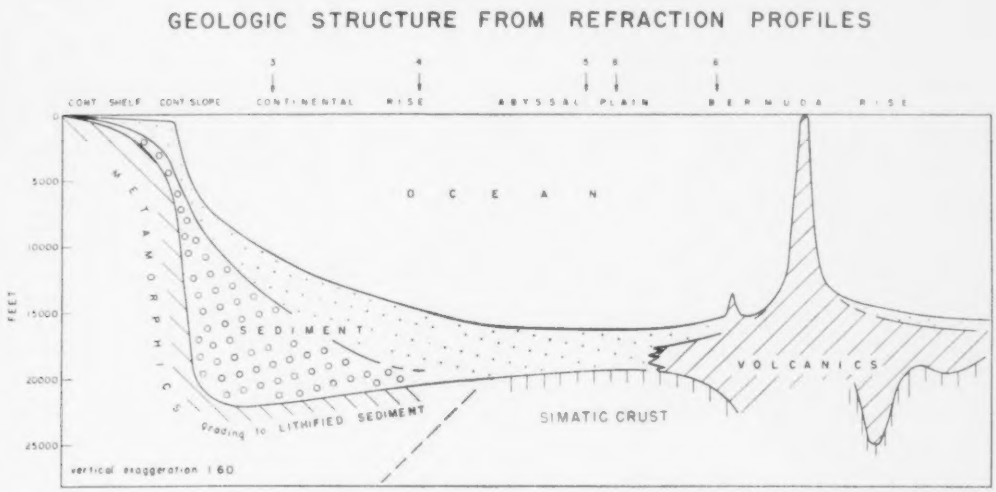


Fig. 3. Geologic structure from refraction profiles.

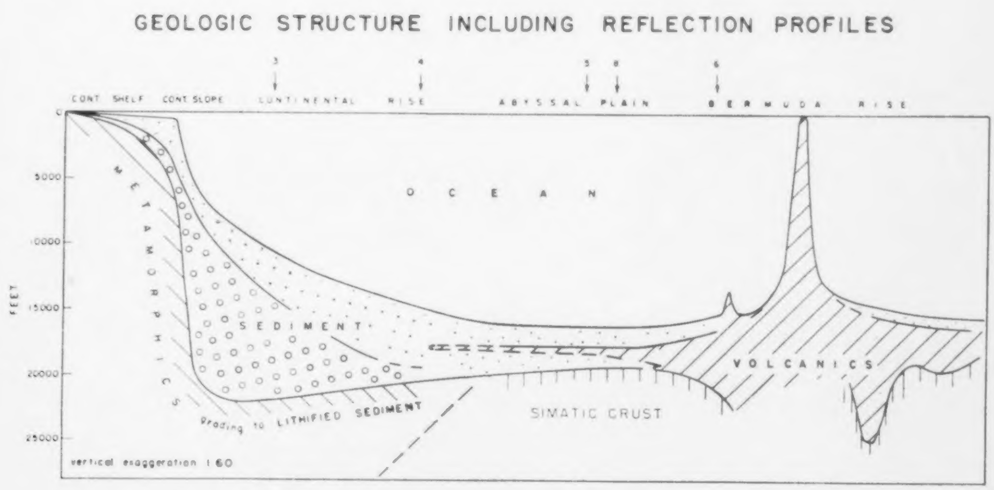


Fig. 4. Geologic structure including reflection profiles.

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Proposed names of features on the deep-sea floor

2. General principles governing the allocation of names

JOHN D. H. WISEMAN and CAMERON D. OVEY

Summary—A list of general principles developed by the British National Committee on the Nomenclature of Ocean Bottom Features is given. Reasoned criticism of these proposals would be welcomed, especially if they have the support of a national group.

INTRODUCTION

THE British National Committee on the Nomenclature of Ocean Bottom Features has under review the names for the more important deep-sea features, and a preliminary list has been given for the Pacific Ocean (WISEMAN and OVEY, 1955). During the course of this work, consideration has been given to the general principles governing the allocation of names to deep-sea features, in the hope that a rational, simple and generally acceptable system of allocating names could be developed. Although a few of these general principles have been discussed in this journal (WISEMAN and OVEY, 1953 and 1955), no comprehensive list has yet been published. As names are an essential tool for the scientific interpretation and description of bathymetric surveys, the British National Committee considers that confusion would be avoided and international agreement made possible if other workers in this field had the opportunity of studying and criticizing its proposals. The British National Committee would therefore welcome reasoned criticisms, especially if they have the support of a group of scientists.

PROPOSED PRINCIPLES

1. No feature should be named without adequate reason.
2. When a name is proposed for a feature, a comprehensive definition should be given. Names which have either been used for similar features or have a confusing meaning should be avoided.
3. It is desirable on general grounds that any proposed name for a feature outside the 100 fm line should, in the first instance, be brought before a national group prior to publication.
4. It is important that, wherever possible, names should have geographical significance.
5. When there is no suitable geographical name for small features, a ship's or personal name which has not previously been used may be given.
6. A newly discovered elevation of more than 3,000 ft should be unnamed and classed as a seahigh unless an adequate survey has been made. Reference should then be made to it by a code number based on the following system:

   Each feature should be given a number consisting of the mean geographical co-ordinates,

prefixed by an abbreviation indicating the quadrant. If sufficient information is available to indicate the possible character of the feature then a suffix may be attached to the code number. The following are suggested: (m) for seamount, (t) for tablemount, (b) for oceanic bank, (p) for seapeak and (r) for ridge or rise.

For example SW 5930 – 6857 (p) = Seapeak at 59° 30′S 68° 57W.

7. A seamount or seaknoll should not be named unless isolation has been fully established.

8. Names of ridges and rises should preferably be simple and descriptive of their geographical extent.

(a) The length of a ridge or rise can in some cases be conveniently given by two geographical names:

Eauripik – New Guinea Rise.
Socotra – Chagos Ridge.

In such instances it is a useful convention to read from west to east, or for features extending due north and south, to quote the more northerly first.

(b) The length of a ridge or rise can in some cases be given by a single geographical name:

Aleutian Ridge, Kuril Ridge, Marianas Ridge, New Hebrides Ridge.

(c) The approximate location and length of a ridge or rise can in some cases be shown by such devices as:

Atlantic – Antarctic Ridge, Scotia Ridge (boundary of Scotia Sea), Mid-Atlantic Ridge.

9. When it is impossible – or, on the grounds of simplicity, it is undesirable – to indicate the length of a ridge or rise, the feature in question may be named from an island, shaol or bank on the ridge or rise, or by one of the terminating points:

Norfolk Island Ridge, Hunter Island Ridge, Lord Howe Rise, Pandora Ridge, South Honshu Ridge, South Fiji Ridge, South Tasmania Ridge.

10. Simplification can be achieved by using the geographical name of a ridge for a nearby basin or trench :

Aleutian Ridge, Aleutian Basin, Aleutian Trench.
New Hebrides Ridge, New Hebrides Basin, New Hebrides Trench.
Marianas Ridge, Marianas Basin, Marianas Trench.

11. Small basins or troughs can frequently be named from one of the limiting features:

Falcon Trough (after Falcon Ridge).

12. Names should not include unnecessary words, such as island, sea, etc. These should only be included when there is likely to be possible confusion.

13. As the ultimate aim is to develop a rational and easily assimilated list of names, which is an essential descriptive tool, the " law of priority " cannot be strictly applied if the existing name is not in general accordance with the principles of nomenclature.

14. The use of the existing personal or ships' names given to areas of the sea-floor deeper than 3,000 fms should generally fall into abeyance. A ship's or a personal name may, however, be given to a few of the deepest soundings:

Challenger Depth – 5,940 fms, 10,863 m, 11°19′N 142°15′E.
Horizon Depth – 5,814 fms, 10,633 m, 23°15.5′S 174°46.5′E.
Cape Johnson Depth – 5,740 fms, 10,497 m, 10°27′N 126°36′E.
Vityaz Depth – 5,674 fms, 10,377 m, 44°17.6′N 150°30.1′E.

15. Personal or ships' names should not at this stage be given to specific areas within basins or trenches, as in descriptive work such areas can with little extra trouble to the author be referred to by a suitable phrase, or notation on the bathymetric chart. If ships' or personal names are allocated to such areas, although the author may overcome some slight inconvenience in his paper, no generally useful purpose would be served, as there would be few who would remember the geographical limits of a non-geographical name; further, with an increase in the number of soundings, the depth limits will in the course of time be altered.

British Museum (Natural History), London.

Department of Geography, Cambridge.

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Directional echo sounding

By H. F. P. Herdman

Summary—A short account of an experiment to improve the directional quality of deep water echo sounding equipment. A comparison is made between the results obtained with the pre-war sonic deep water echo sounding set then fitted, and the present-day supersonic type of equipment now installed in the R.R.S. *Discovery II*. Methods of stabilizing the transmitter and receiver to overcome the effect of rolling on the narrower and, hence, more directional beam of sound now transmitted, are discussed. A short description of the method adopted is followed by particulars of an attempt to increase the amount of energy transmitted, by a reduction in thickness of the hull plating, in way of the stabilized transmitter and receiver.

Experiments are now being made in the R.R.S. *Discovery II* in an attempt to improve not only the directional quality of the deep-water echo-sounding equipment but also the strength of transmission and reception. Before decribing these experiments – which are being made in collaboration with Messrs. Kelvin & Hughes – mention should be made of the different types of deep water equipment which have been, and are now fitted. In addition some comparison should be made between the performance of the sonic deep-water equipment carried until the outbreak of war in 1939, and that of the supersonic magnetostriction type of apparatus by which it has been superseded.

The original deep-water echo-sounder installed in the *Discovery II* in 1929 was the British Admiralty Deep-Sea Pattern, made by H. Hughes & Son. This was a sonic instrument of the listening type, operating at a frequency of 2,000 cycles/sec. Transmissions were effected by a compressed air-powered hammer which struck a diaphragm mounted on a water tank secured to the hull and the receiving hydrophone was fitted externally through a sluice valve. Between 1930 and 1932 we obtained with this apparatus a number of soundings greater than 4,000 fm (7,315 m) in the South Sandwich Trench. The greatest corrected depth recorded was 4,480 fm (8,193 m). In 1933 the listening-type receiver was supplemented by an " Acadia " type electrolytic recorder with a phasing system operating to any depth by 100 fathom steps. Apart from replacements due to fair wear and tear, this equipment was in constant use until the outbreak of war in 1939. Shortly afterwards it was removed and scrapped.

When the *Discovery II* was recommissioned as a research vessel in 1950, and since the original type of deep-water echo-sounder was no longer made, a Kelvin & Hughes Type 21E echo-sounder was fitted. This is a magnetostriction type, operating at a frequency of 10 kc/sec., and recording electrolytically on paper in fathoms, or fathoms x 10. More recently another recorder has been added, which records on metallized paper (" Teledeltos " recording). Transmitter and receiver were both fitted in tanks *inside* the shell plating (0.43″ thick, at the positions concerned). Theoretically, the depth-range is unlimited – in practice, the greatest depth recorded so far has been 3,733 fm (6,827 m). It is only fair, though, to add that, since this new set was fitted, the ship has only passed over such very deep water on one brief

occasion – when crossing the South Sandwich Trench in very poor sounding weather, during work on the Antarctic ice-edge in the winter of 1951.

With sonic equipment – where a hammer strikes a plate in contact with the sea – the sound-waves are projected with a considerable amount of " spread " ; observations made during survey work indicated that the semi-angle of spread might be roughly 45°, but the weakness of the " fringe " echoes supports the theory that, for this particular hammer, the greater part of the transmitted sound was projected towards the bottom (HERDMAN, 1948). The magnetostriction, or supersonic set, fitted in 1950, transmits a more compact beam, or rather, cone of sound, in which the energy falls to half value at an angle of 8° to the axis, and is zero at 21°.

With the original sonic deep-water set the rolling of the ship – unless sufficiently vigorous to set up interference in the microphone or cause water-noises, which masked the echo – was not a serious hindrance to recording echoes. As already mentioned the spread of the transmission was considerable and the angle at which the returning sound waves struck the face of the hydrophone was not very critical. If the sea-bed was level echoes recorded under these conditions were probably the true depth but – if the bottom was distinctly irregular then – as the strongest echo (normally taken as the sounding) was almost certainly returning from the nearest point – which might or might not be directly under the ship – the contour of the bottom shown on the record was probably not truly representative. The echoes received from the more-directional transmissions of the present-day supersonic equipment certainly give a more correct record of the shape of the bottom, but there are disadvantages. In the first instance, when sounding up (or down) a steep slope there is, assuming specular reflexion, the danger that, if the slope angle is greater than the semi-angle of spread of the transmissions, the echo will not be received.

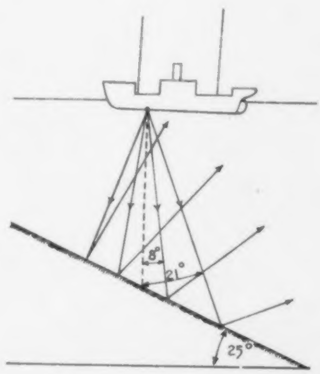

Fig. 1. Diagrammatic representation of sounding up a steep slope.

In practice, however, a number of echoes are received; some faint, probably from transmissions beyond the normally effective angle of spread ; others stronger, probably from irregularities in the surface of the slope. Under these conditions lengthening of the echo-trace is often observed.

Another instance of the effect of spread is shown in Figs. 2, 3 and 4 – which comprise 3 sections of a recording made at depths between 975 and 1,175 fathoms (corrected), on the Mid-Atlantic Ridge, in June, 1954, with the ship hove-to on Station 3121*. The bottom here is very diverse in character and it will be clearly seen that it is quite impossible to say which echo-trace represents the true depth directly under the ship.

A more serious disadvantage of the reduction of spread of the transmissions is the effect set up by the movement of a small ship, especially when the ship is rolling,

* Stations in the *Discovery II* are worked normally with the ship hove-to head to wind and, so far as is possible, making no headway through the water. Nevertheless, if there is any appreciable current or drift in the surface layer, there will be a comparable movement of the ship over the bottom, which will, when the bottom is very irregular, show markedly on the echo-trace.

Even in moderate weather a ship constructed on the lines of the *Discovery II* will roll extensively and thus there are the possibilities either that the transmissions may be directed well off the direct path to the bottom, so that the returning echo misses the receiver or, if the transmissions were made with the ship on an even keel that, by the time the echoes return, the ship may have rolled to an extent that the signals will arrive at the receiver when the latter is at such an angle that it is insensitive to them.

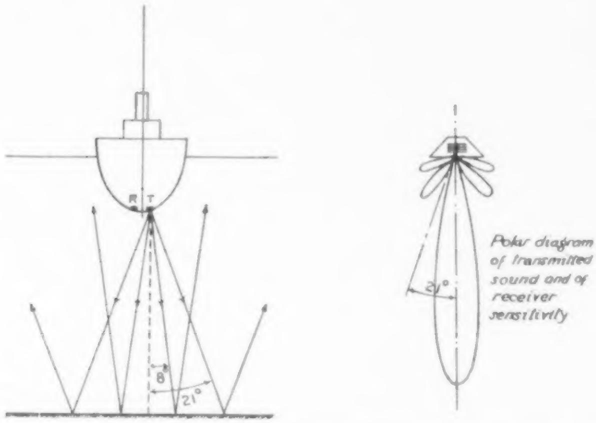

Fig. 5 (a). Diagrammatic representation of sounding with ship on an even keel.

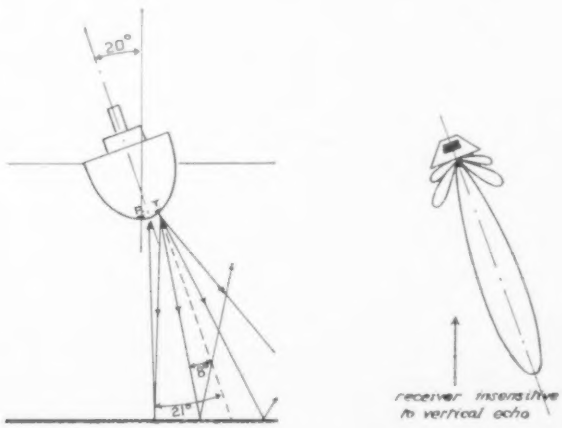

Fig. 5 (b). Diagrammatic representation of sounding when ship is rolling 20° from vertical.

If the narrow, directional beam of transmission is to be retained – and this is most desirable – then stabilization of both transmitter and receiver to the roll of the ship would seem to be the solution. The effect of pitching can be ignored as when a ship is pitching heavily in a head sea, so much aeration is set up under the hull forward (where the transmitter and receiver normally are fitted) that not only are the echoes

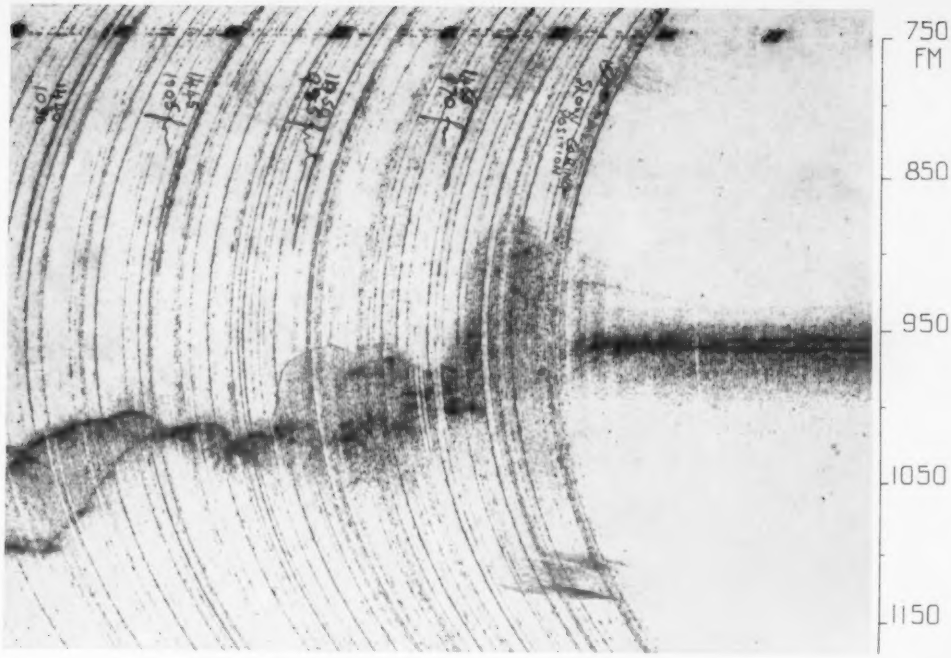

Fig. 2. Echo-trace approaching, and at beginning of Station 3121.

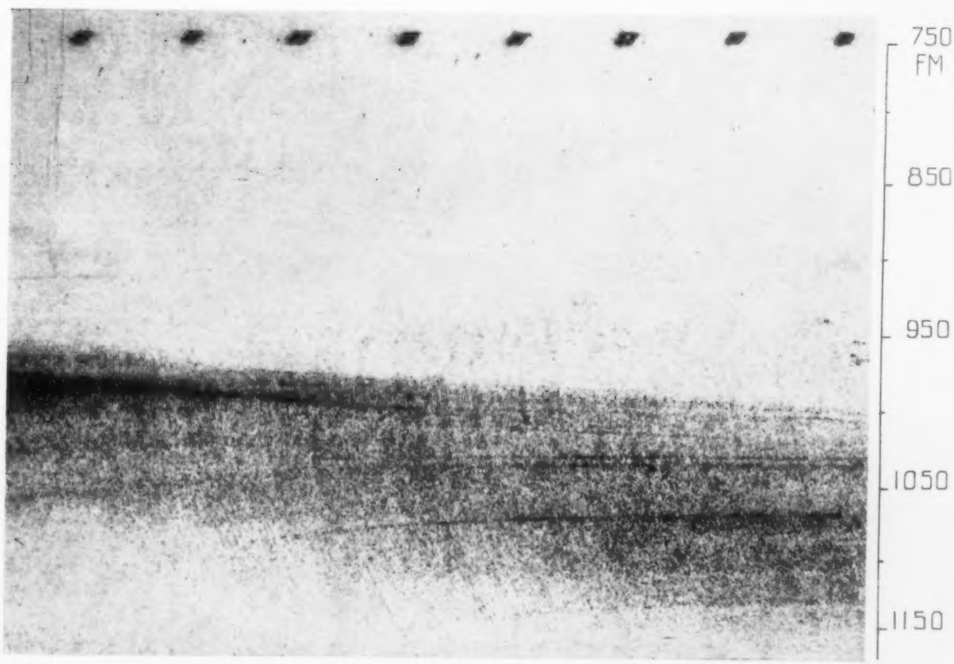

Fig. 3. Echo-trace with ship hove-to on Station 3121 (wind 280° (true), force 4 (11-16 kn.), sea 280° (true) – height 2-3 ft.).

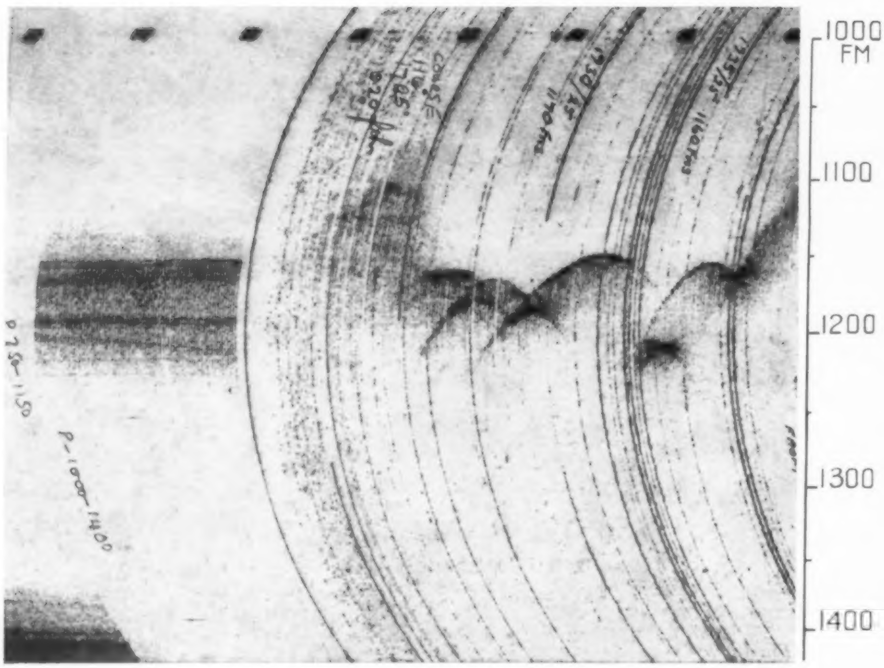

Fig. 4. Echo-trace at end of Station 3121, and when under way after station.

obscured by air-bubbles and water-noise, but the outgoing sound-waves are themselves blanketed. In any event, compensation for pitching would not have been practicable in the *Discovery II* without major structural alterations which were unlikely to be approved by Lloyd's Register of Shipping.

Three methods of stabilizing the transmitter and receiver for athwartships motion were considered during the refit of the ship in 1953-4 ; two of these implied control of the movement, the other did not.

The methods were : (1) gyroscopic control, (2) control by electronic methods and, (3) the simple but uncontrolled method of mounting the reflectors so that they could swing freely in the athwartships line. Whereas methods (1) and (2) would have controlled the movement of the transmitter and receiver accurately, not only was the cost of providing such equipment likely to have been heavy, but there would have been considerable delay in making it and fitting it in the ship. On the other hand the alterations required, if the third method was adopted, were not extensive and the equipment could almost certainly be ready for trials on completion of the refit. A disadvantage of this method would be, of course, the probable lag in the swing of the oscillators ; this was, however, not expected to exceed 5° (much less than the degree of roll for which compensation was desired) and thus, in view of the very much experimental nature of the trials, could be accepted.

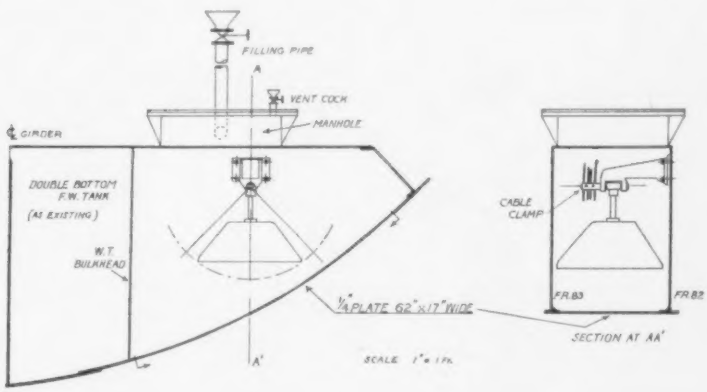

Fig. 6. General arrangement of stabilized oscillators – as fitted in double-bottom tanks.

Method (3) was therefore adopted and, as shown in Fig. 6, a pair of type 21E oscillators (exactly similar to those already fitted in the normal way) were mounted in two special watertight tanks, constructed by isolating part of the forward double-bottom fresh-water tanks to port and starboard of the centre line, 3 ft. 7in. forward of the existing oscillators. Arrangements were also made to ensure that the oscillator tanks were kept absolutely full of water.

The existing Type 21E fixed transmitter and the stabilized instrument now fitted were connected, via a change-over switch, to a common transmission unit. The two receivers were similarly connected – through a separate switch – to the 21E and 26E recorders. Comparison of the two systems could not, therefore, be made simultaneously on two recorders but as weather conditions and the state of the sea do not

usually alter in a matter of seconds, little information of interest was lost. The superiority of the stabilized system was markedly shown on most occasions when the ship was rolling moderately ; the echo-trace was almost continuous and considerably less gain was required to give the same intensity of echo-marking as recorded with the fixed oscillators.

Both the fixed and stabilized oscillators in the *Discovery II* have been transmitting and receiving through the full thickness of the hull plating (0.43″ or 10·9 mm), with a consequent and – probably considerable – loss of energy. The ratio of thickness of hull plating to the wavelength in the steel of the plating is a very important factor in echo-sounding ; it must be kept as small as possible consistent with the requirements of safety, and a plate thickness of 0·25″ (6·35 mm) is recommended by Messrs. Kelvin & Hughes for a standard installation. Permission was sought therefore from Lloyd's Register of Shipping for a reduction in thickness of the hull plating in way of the stabilized oscillator compartments. Subject to certain safeguards, approval to fit plating 0·25″ (6·35 mm) thick was obtained, and an area of the original hull plating in each tank, 62″ x 17″ (1·57 x 0·43 m), has recently been cut out and replaced by the thinner plating – welded flush with the outer side of the original plating. All external laps in way of the stabilized compartments have also been faired by welding.

Owing to certain technical difficulties arising from the special construction of the *Discovery II*, it was not practicable at the same time to arrange for plating of the same thickness to be fitted under the standard tanks of the original Type 21E fixed oscillators. A complete comparison between the fixed and stabilized systems will thus not be possible but, nevertheless, the modification is expected to lead to the improved performance of the stabilized equipment.

This paper has been read in manuscript by Dr. W. HALLIDAY (Chief Physicist, Acoustics Division) and Mr. C. S. SPARLING, of Kelvin and Hughes Ltd. ; to them I am grateful for advice and valuable suggestions. At the same time I should also like to express my appreciation of the help so freely given to me by my colleague, Dr. J. S. SWALLOW.

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The General Bathymetric Chart of the Oceans

JOHN D. H. WISEMAN and CAMERON D. OVEY

Summary—A brief historical account is given of the General Bathymetric Chart. The International Committee on the Nomenclature of Ocean Bottom Features considered at its Monaco meeting in September 1954 various proposals for the improvement of it. As the final sheets of the third edition have gone to press, the International Committee considers that users of the General Bathymetric Chart should have the opportunity of studying and criticizing its proposals. The Committee would welcome reasoned criticism, especially if it has the support of a national group. These should be sent at an early date to the Joint Secretaries of the Committee, Vice-Adml. J. D. NARES and Mr. C. D. OVEY.

HISTORY

IT IS fifty-one years ago since the first edition of the General Bathymetric Chart was presented to the Académie des Sciences at Paris (THOULET and SAUERWEIN, 1904), and approved by the Eighth International Geographical Congress at Washington (*Rept. of Eighth Internat. Geogr. Cong., Washington*, 1904, p. 108). The idea of a General Bathymetric Chart was first put forward at the Seventh International Geographical Congress at Berlin in 1899 (KRÜMMEL, 1901, p. 386; MILL, 1901, p. 392) when a nomenclature committee composed of BARON DE RICHTHOFEN (President), S.A.S. Prince ALBERT I of Monaco, Prof. O. KRÜMMEL, Adml. MAKAROFF, Dr. H. R. MILL, Sir JOHN MURRAY, FRIDTJOF NANSEN, Prof. O. PETTERSSON, Prof. A. SUPAN and Prof. J. THOULET was given the task of publishing by the time of the Washington 1904 Congress a bathymetric chart of the oceans. This committee assembled at Wiesbaden in April 1903 to consider proposals put forward by THOULET (1904). It was agreed that the chart should consist of 24 sheets based on the Greenwich meridian; that sixteen of the sheets (0°-72°) should be on the Mercator projection with a scale of 1 : 10,000,000 at the Equator, and that the eight remaining polar sheets should be on a gnomonic projection. S.A.S. Prince ALBERT I of Monaco undertook the preparation of this chart. Work was begun in June 1903 by seven draughtsmen who rapidly completed it. The documents consulted were generally British Admiralty Charts and the reports of expeditions (THOULET, 1905, p. 442).

The improvements in the second edition were based on the recommendations of a committee which met at Monaco in April 1910 (BOURÉE, 1910). Although the projection and the geographical limits of the sheets remained the same, the land relief was shown by coloured layers, and a depth legend was included in the margin of each sheet. Work was started in 1910, and the last sheet to be published was in 1927. The new soundings used in the compilation of each are given in the publications of the Cabinet Scientifique de S.A.S. le Prince de Monaco.

In 1929 the International Hydrographic Conference instructed the International Hydrographic Bureau to centralize oceanic soundings, and to keep the General Bathymetric Chart up-to-date, as the Cabinet Scientifique de S.A.S. le Prince de Monaco had been disbanded. M. P. DE VANSSAY DE BLAVOUS communicated to the International Union of Geodesy and Geophysics, at Oslo in 1930, the International

Hydrographic Bureau's proposals, and invited scientists to submit recommendations (*Internat. Hydr. Bull.*, 1931, **7**, p. 168-196, and p. 213-215). The first sheet (A_I) of the third edition was issued in 1935, and the soundings were recorded on plotting sheets generally on a scale of 1 : 1,000,000 (BENCKER, 1930, p. 68). This innovation permitted the plotting of soundings on a scale appropriate to the general accuracy of their positions. In view of the fact that the final sheets (B'_{II}, C'_{II}, and C'_I) have gone to press, it is desirable that users of the General Bathymetric Chart should have the opportunity of studying and criticizing the recommendations made by the International Nomenclature Committee before final decisions concerning the form of the fourth edition of the General Bathymetric Chart are taken by the International Hydrographic Bureau.

PRELIMINARY SUGGESTIONS

At the VIIIth Assembly of the International Union of Geodesy and Geophysics at Oslo in 1948, the Association of Physical Oceanography re-established a nomenclature committee. This committee was instructed amongst its other duties 'to consider the methods of presentation of topographic data on bathymetric charts.' A preliminary report based on meetings at Brussels in 1951 has been published (*Bull. d'Inform. de l'U.G.G.I.*, 1953, **2**, no. 1, p. 128). As a result of these preliminary recommendations experimental changes have been made in the recently issued sheets of the General Bathymetric Chart, and copies of the Bureau's plotting sheets are now available at cost price. The importance of up-to-date bathymetric charts was recognised by a resolution submitted to the General Assembly of the International Union of Geodesy and Geophysics (*Bull. d'Inform. de l'U.G.G.I.*, 1952, no. 1, p. 16). The Joint Commission on Oceanography in 1952 (*Bull. d'Inform. de l'U.G.G.I.*, 1953, **2**, no. 2, p. 375) suggested that the General Bathymetric Chart should be kept more up-to-date, and that a new edition should be published every five years. As a result of the Commission's activities the International Hydrographic Bureau has been given, for a limited period, a grant from the International Council of Scientific Unions so as to enable the Bureau to print one additional chart per year. The British Nomenclature Committee has, with the help of outside experts, considered improvements which could reasonably be made to the General Bathymetric Chart, and, in the summer of 1954 it submitted a paper to the International Nomenclature Committee.* This paper was considered on the 9 and 10 September 1954, and the following recommendations were made.

RECOMMENDATIONS

1. *Contours*

The Committee considers that generally there is at present, insufficient bathymetric information to produce a fully contoured chart. The contouring intervals (200 m, 500 m, 1,000 m, 2,000 m, etc.) are considered satisfactory for the majority of the sheets, but in certain well sounded areas – e.g. A_I – it may be possible to insert

* Besides members of the Committee (Dr. J. D. H. WISEMAN, Chairman, Vice-Adml. J. D. NARES and Mr. C. D. OVEY, Joint Secretaries, and Dr. K. O. EMERY) who attended this meeting the following were present: Capt. H. L. G. BENCKER, Prof. J. BOUCART, Dr. A. F. BRUUN, Dr. R. S. DIETZ, Cdr. G. P. D. HALL, Mr. G. LIEFSON, Rear-Adml. C. L. NICHOLS, Cdr. E. R. SHERIDAN, Rear-Adml. R. F. A. STUDDS.

intermediate contours at 500 m intervals. The Committee urges that there should be three types of contours:—

(1) Firm when well sounded.

(2) Dotted (with dots wider apart than those shown on the new revision of sheet B'_I when based on a few soundings).

(3) When the bottom topography is virtually unknown the general surmised change of depth should be indicated by colour grades without the insertion of dotted contours.

The Committee suggests that it would be helpful to users of the chart to include in the margin of each sheet a brief explanation of the significance of the different types of contours.

2. *Projection*

The Committee recommends the continued use of the Mercator projection (Scale 1 : 10,000,000 at the Equator) for the sheets A and A' (0°-46°40′). North and south of this the projection should, in the Committee's view, be stereographic but in the northern hemisphere it may be necessary to issue in addition certain sheets on the Mercator projection. Alternative projections – e.g. the gnomonic and zenithal equidistant, were considered, but the great advantage of the stereographic projection is that, like the Mercator projection, it is conformal. The Committee suggests that the northerly and southerly sheets, which for convenience are called the polar sheets, should preferably have a " rolling fit " with the Mercator sheets, i.e. the scale at 46°40′ should be 1 : 6,862,416. This would require a circle with a 25-inch radius, which would be too large for the existing standard sheet. To overcome this difficulty the Committee suggests that the circle should be divided into two semi-circles; i.e. there would be two north polar sheets and two south polar sheets. The complete edition would then comprise

No. of sheets	*Latitude*	*Projection*	*Scale*
8	0° 46°40′	Mercator	1 : 10,000,000 1 : 6,862,416
4	46°40′ 90°	Stereographic	1 : 6,862,416 1 : 7,945,500

The third edition consists of 16 Mercator sheets extending to 72° latitude and 8 polar sheets (gnomonic projection).

Advantages of a stereographic projection (90°-46°40′)

(1) With existing financial resources, which permits the printing of two sheets per year, a new edition should be completed in six years instead of at least eight with the existing 16 sheets on the Mercator projection. Thus without any additional printing expenditure the General Bathymetric Chart could be kept more up-to-date.

(2) The scale variations would be small, 1 : 10,000,000 to 1 : 6,862,416 and the present wide range is from 1 : 10,000,000 to 1 : 3,100,000 would be avoided.

(3) The stereographic projection, like the Mercator is a conformal projection – that is to say, at any point, the scale is the same in all directions.

(4) The relationship of the deep-sea features in higher latitudes would be more acceptable to scientists.

Disadvantages of stereographic projection (90°-46°40′)

(1) Northern maritime nations have traditionally a bias for the Mercator projection, and it might be necessary to issue in addition certain sheets on a Mercator projection because a change to a stereographic projection might not be welcomed by a majority of the State Members of the International Hydrographic Bureau.

(2) The International Hydrographic Bureau with its limited staff would have additional work in the preparation of the stereographic sheets.

(3) The stereographic sheets would be of little navigational use – (a purpose for which they are not intended).

The Committee, realizing the great amount of extra work involved in changing to a stereographic projection, considers that the matter should be carefully investigated by the Hydrographers before a final decision is taken.

3. *Soundings*

The Committee agrees with the recent policy of the International Hydrographic Bureau of reducing the number of soundings on each sheet. For example the recently published sheet B'_I has only 802 soundings. In the Committee's view the clarity of this sheet is greatly increased. The Committee does not now, however, concur with the original 1951 Brussels recommendation that only the maximum and minimum soundings should be inserted, as such a policy could only apply to a fully contoured chart, which cannot be constructed at this stage. The Committee feels that the number of soundings could be increased with advantage over this figure without loss of clarity, and urges the scientific importance of indicating important lines of soundings possibly by a suitable dotted line which must be distinct from a contour, and with significant changes of depth recorded. It is thought that the reliability of the sheet would then be clearer; the specialist would then realize where he could obtain detailed information from the International Hydrographic Bureau's plotting sheets, and the scarcity of reliable sounding lines would be self-evident in many of the sheets.

4. *Chartlet showing density of soundings*

A small chartlet showing the density of soundings, possibly divided in squares, should be included in the pamphlet that accompanies each sheet and printed in the margin of each.

5. *Graticule*

The printed graticules should be thinner; the 2° or 1° squares should not be included on the land areas; the intersection of the meridians and parallels should be removed from the sea areas; and the ticks to indicate 1° should be kept on the graticule.

6. *Graduation*

It was considered by the Committee that the sheets would be greatly improved by the addition of a skeleton graduation round the border, as well as along two diameters at right angles in the case of the polar sheets.

7. *Names of deep-sea features*

The Committee considers that internationally-agreed names should be included on each sheet. It was also suggested that the names of deep-sea features should be printed in a totally different type so as to avoid confusion with the names of oceans, etc.

8. *Colour layers*

The Committee was of the opinion that economy might be effected by a wider use of screens. It would seem possible that the same number of contours could be shown by four basic blues instead of six, and three basic browns instead of four. This would mean a saving of three printing plates and three impressions, which should result in a considerable economy.

9. *Increase of sales and cost*

The Committee urges that scientists interested in deep-sea research should promote the sale of the sheets to oceanographical departments, geographical departments of universities and libraries. It is the Committee's view that increasing efforts should be made to augment the sale of the chart.

10. *General*

The Committee commends the recent policy of the International Hydrographic Bureau of submitting before publication the proof of a sheet, wherever possible, to an outside specialist, and of making available copies of their plotting sheets. Finally the Committee desires to thank the International Hydrographic Bureau for helpful discussions about the difficult problems involved in the production of the General Bathymetric Chart.

British Museum (Natural History), London.

Department of Geography, Cambridge.

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Quelques Résultats Géologiques de la campagne de la "Calypso" en Mer Rouge (1951-1952)

WLADIMIR D. NESTEROFF

Summary—Transverse profiles through the Red Sea have confirmed its graben structure. The elevated reefs suggest a distinction between types of movement: those linked with tectonics, and those related to world oscillations of sea level.

In explaning the origin of the Red Sea reefs, several theories must be taken into consideration; for the most part, the Darwinian theory is satisfactory, especially in view of the graben subsidence in the centre of the rift.

Sedimentation in the Red Sea is mostly of pelagic character, but the reefs introduce organic detritus. Sands are largely due to the feeding activity of reef-browsing fishes. Coral muds represent the finer portion of the organogenic clastics. The metabolism of micro-organisms also plays a part in the formation of beachrock. Active marine erosion was not recognized by the author beneath the surface of the Red Sea. All reef forms: lagoons, coral-knolls, caverns, channels through barrier reefs are attributed to diffierential reef growth.

The author estimates present reefs to be fully active. Decadent reefs are due to poor water renewal; unfortunately these are the most frequently visited.

CET article résume (voir NESTEROFF, 1955a) certains résultats géologiques de la première campagne du bâtiment océanographique "Calypso" en Mer Rouge (1951-1952). Il tentera de mettre en lumière la structure profonde de cette mer et des édifices coralliens qui lui sont associés. Notre expédition travailla surtout dans le banc Farsan Nord (côte arabe, 20° parallèle nord) mais visita aussi nombre de récifs disséminés dans la Mer Rouge.

L'utilisation intensive par les chercheurs du scaphandre autonome COUSTEAU-GAGNAN,* parallèlement aux méthodes de l'océanographie classique (dragages, carottages, écho-sondages, etc.) représente l'innovation capitale de cette expédition. Son emploi s'est révélé d'un grand intérêt pour l'interprétation des théories récifales. Il a considérablement amélioré la précision et l'ampleur des observations sur place, plaçant l'observateur sous-marin dans des conditions assez comparables à celles du géologue terrestre.

STRUCTURE DE LA MER ROUGE

1. *Forme Générale*

Il est très difficile de parler de plateau continental lorsqu'il s'agit de la Mer Rouge. Si nous nous reportons aux coupes transversales de cette mer (Fig. 1) établies lors de notre expédition ainsi qu'aux cartes marines, nous trouvons l'isobathe 500 m à une distance variant de quelques centaines de mètres à quelques kilomètres du rivage. Cela nous conduit plutôt à attribuer très schématiquement une forme en auge à la Mer Rouge.

Dotée d'un fond sensiblement plat vers les 1000 mètres, ses bords se relèvent très rapidement, voir même verticalment. Dans la partie nord (N), la chute se produit

* Fabriqué également aux Etats-Unis, où il est vendu sous le nom de "Aqualung."

souvent en 2 ou 3 marches d'escaliers (Crossland et Badr, 1939) alors qu'au centre on observe souvent des dénivellations brutales de 500 mètres (Fig. 1, points E H J). Le fond de l'auge est fortement bosselé, surtout dans le nord et présente de nombreux creux et pitons.

Au sud du 21° parallèle N, un fossé, large de 40 km, atteignant 1800 m de profondeur, affecte le centre de cette auge. Ce fossé est lui-même creusé d'un étroit sillon de 6 à 8 km de large qui atteint 2.240 m. Ce schéma très général, n'est pas valable au sud (S) du 17° parallèle N ou les structures se resserrent, les fonds se relèvent (Kuenen, 1935) et où malheureusement nous n'avons pas pu exécuter de coupes.

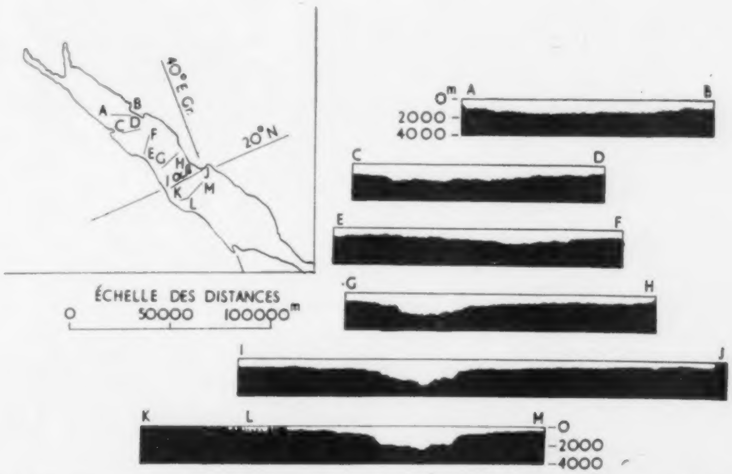

Fig. 1. Coupes transversales de la Mer Rouge. Echelle des profondeurs x 5. Le carton indique la position des coupes.

Nous avons bien là l'image d'un graben, dont les compartiments les plus centraux se sont effondrés plus profondément que les autres. Cette image se précise encore lorsqu'on considère les montagnes qui bordent la Mer Rouge à l'est et à l'ouest et constituent les compartiments externes du graben. Ces formes, en particulier le fossé central, plaideraient en faveur d'une forme d'effondrement de clef de voûte de forces de détente.

La disparition du fossé central au nord du 21° parallèle peut s'interpréter soit par un jeu de failles en ciseaux, permettant aux compartiments centraux de s'effondrer au sud, alors qu'ils restent en place au nord, soit par un remplissage dû à des épanchements volcaniques sous-marin de la partie nord de ce fossé (Tazieff, 1952).

Ce graben comporte 2 directions principales de failles NNW-SSE (erythréenne) et N-S. Ce sont les directions mêmes des lignes du rivage ce qui conduirait à attribuer à celles-ci une origine tectonique.

Nous avons plus particulièrement étudié le banc Farsan Nord et l'archipel Souakim. Ces 2 entités sont d'un grand intérêt pour la compréhension de la structure de la Mer Rouge. Le banc Farsan est un classique de la Mer Rouge, l'archipel Souakim une structure exceptionnelle.

2. *Le banc Farsan*

Les cartes marines présentent le banc Farsan N (côte arabe, 20° parallèle N) simplement comme une zone de dangers. Il se décompose toutefois du point de vue structural en 2 entités bien distinctes.

1° La prolongation de la plaine côtière (Tihama). C'est une plateforme immergée par 60-80 m, recouverte de nombreux pâtés coralliens (shoal-reefs), souvent anastomosés. La côte est bordée de récifs frangeants qui introduisent une dénivellation brusque de 20 à 40 m entre la plaine littorale et cette plateforme.

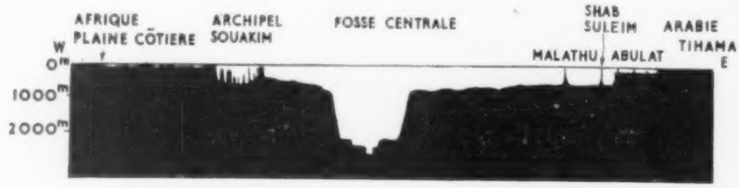

Fig. 2. Coupe transversale schématique, perpendiculairement a l'axe de la Mer Rouge, a la hauteur du 19 e parallèle. Echelle des profondeurs x 20. On voit les pitons coralliens s'installer sur la platforme 500-900 m a côté d'Abulat, ainsi que dans le synclinal de l'Archipel Souakim.

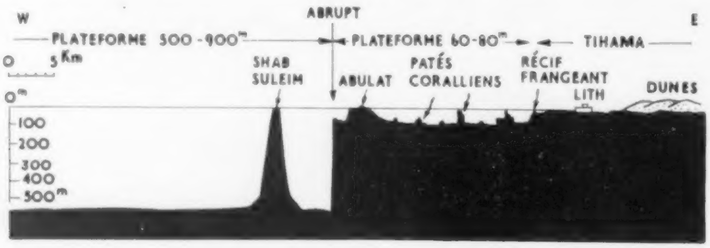

Fig. 3. Coupe schématique du banc Farsan Nord. On voit le décrochement entre la plate-forme 60-80 m suivie de la plaine côtière a l'Est, et la plate-forme 500-900 m du coté du large a l'Ouest. Cette dernière plate-forme porte de grands pitons coralliens (ici Schab Suleim).

2° La plateforme 500-900 m qui correspond au fond plat de la Mer Rouge. Dans sa partie proche du littoral (fond de 500 m) elle porte des édifices coralliens peu nombreux et dispersés. Il s'agit de récifs tabulaires qui se présentent sous forme de pitons ou crêtes. Cette disposition rappelle certains récifs du Sahul Shelf australien (TEICHERT et FAIRBRIDGE, 1948).

Un abrupt vertical de 500 m sépare ces 2 plate-formes (Figs 2 et 3). Sa direction erythréenne (NW-SE) correspond à l'une des deux directions de fracture de la Mer Rouge. Il est logique d'interpréter cette structure par une faille (GUILCHER, 1955; TAZIEFF, 1952).

Cependant certains faits nous invitent à quelque réflexion. L'absolue verticalité de l'abrupt apparente son profil bien plus à celui des pitons coralliens qu'à celui des compartiments séparés par un rejet de faille, telles les failles délimitant la fosse centrale (Fig. 1, couple LM). Cette faille affecte, au moins dans sa partie supérieure, des dépôts détritiques ou pélagiques plus ou moins consolidés qui formeraient un talus d'éboulis. Le bord de l'abrupt séparant les 2 plateaux porte un léger ressaut d'origine corallienne d'une vingtaine de mètres, qui surhausse le bord du plateau 60-80 m.

Je proposerais donc une explication légèrement différente. Cet abrupt correspondrait bien à une faille séparant 2 compartiments du graben. Mais le compartiment le plus côtier affecté lui aussi par un mouvement descendans aurait porté un récif frangeant ou barrière qui colonisait son abrupt de faille. Ce récif se serait maintenu près de la surface lors de cette descente et aurait fini par construire l'abrupt que nous observons. Derrière, la sédimentation corallienne et terrigène aurait comblé les vides jusqu'au niveau actuel (plate-forme 60-80 m).

Par contre le compartiment situé plus au large aurait porté à l'origine des édifices coralliens moins nombreux dont certains seulement ont survécu jusqu'au niveau actuel: ce sont les pitons et crêtes de la plateforme 500-900 m.

On peut se demander si cette hypothèse bio-tectonique ne pourrait pas s'appliquer à la plupart des côtes de la Mer Rouge; en effet celles-ci suivent sensiblement les directions de fractures et présentent généralment les caractères d'approfondissement brusque et les abrupts verticaux qui semblent cadrer avec cette hypothèse.

3. *L'archipel Souakim*

A la hauteur de l'archipel Souakim (côte ouest, 18° à 19° parallèle) nous n'observons pas l'approfondissement brusque qui est la règle le long des autres côtes de la Mer Rouge. Au contraire, la plaine côtière se prolonge par un grand plan incliné jusqu'aux premiers abrupts limitant le fossé central (Fig. 1, couple K L M). La partie médiane de ce plateau est déprimée par un synclinal large de 35 km environ, dont la profondeur maximum atteint 640 m et qu'un seuil de 380 m de profondeur sépare du fossé central.

Une telle disposition se conçoit facilement si l'on admet une subsidence du flanc ouest du fossé central: ancien plateau continental qui s'approfondit graduellement dans sa partie ouest et se relève vers l'est. Il est interessant de noter que sur le seul tronçon de côte de la Mer Rouge qui ne présente pas l'approfondissement brusque qui caractérise cette mer, par une espèce de compensation prend place une subsidence. Tout se passe comme si une flexure continentale relayait les abrupts de faille.

Du fond de ce synclinal s'élèvent dix pitons de largeur variable aux parois absolument verticales. Il ne nous a pas été possible d'y effectuer de prises d'échantillons. Mais, ces pitons, dont il n'est pas fait mention sur les cartes marines les plus modernes, présentent une certaine analogie avec les structures offertes par le Sahul Shelf (TEICHERT et FAIRBRIDGE, 1948). Leur morphologie permet de leur attribuer une origine madréporique, la verticalité de leur parois et leurs dimensions excluant toute autre explication. La largeur de ces édifices varie de 0,4 à 4 km; sur les bords du synclinal, ils atteignent la surface, mais au centre ils s'arrêtent vers – 250 m.

Quelle que soit la cause de la subsidence, elle semble avoir eu pour conséquence un brusque développement des édifices coralliens qui sont bien plus élévés au centre du synclinal et sur ses flancs que sur la pente non déprimée du plateau continental. Les coraux paraissent avoir cherché à atteindre la surface; s'ils y parviennent sur les bords du synclinal, ils ont été gagnés de vitesse dans l'axe de celui-ci, où la mort des madréporaires a figé les pitons.

Il semble que cette coupe apporte un argument en faveur de la *subsidence* et de l'*instabilité tectonique* dans les facteurs de développement des récifs coralliens, quel qu'ait pu être l'effet d'une oscillation du niveau marin dû à la rétention des eaux par les glaces comme l'avait avancé DALY (1915).

4. *Tectonique et changements de niveau*

Sur tout le pourtour de la Mer Rouge, de nombreux auteurs ont noté des récifs émergés qui ont été portés à des altitudes très variées allant de 4 m (Gravier, 1911) à 230 m (Walther, 1888). Ces récifs présentent souvent des failles et des traces d'efforts tectoniques. A côté de ces structures surélevées, on observe sur les gradins ennoyés de la Mer Rouge, des pitons coralliens qui jaillissent des fonds jusqu'à la surface.

Il semble qu'on puisse attribuer l'émersion ou l'ennoyment de ces récifs aux mouvements tectoniques différentiels des divers compartiments de la Mer Rouge. Les réseaux de failles qui affectent des récifs récemment emergés comme Abulat, indiqueraient l'âge très récent des dernières manifestations tectoniques, alors que les pitons ennoyés montreraient la continuité et la lenteur des mouvements d'affaissement.

A côté de ces mouvements on peut en observer d'autres de moindre envergure. Tous les récifs émergés, aussi bien les récifs du large que les récifs frangeants côtiers portent à altitude fixe (0,5 m – 0,7 m; 1,2-1,4 m et 2,4 à 2,8 m) des encoches qui correspondent à des niveaux de stationnement temporaires de la mer. En outre sur tous les récifs affleurant on trouve des têtes de nègre en place. Ces témoins indiquent que ces récifs émergaient il y a peu de temps, mais ont été érodés depuis. Fait remarquable, tous les récifs portés par les différents compartiments ennoyés du graben ont été affectés de la même manière.

Il y a donc eu récemment dans toute la cuvette de la Mer Rouge un abaissement de niveau de 2 m environ. A quelle origine rapporter ces derniers mouvements ? Il serait sans doute hasardeux de tirer des conclusions d'un si petit nombre de données. La correspondance altimétrique des encoches de la Mer Rouge avec celles signalées dans les autres parties du monde: Indes occidentales (Kuenen, 1933), Australie (Fairbridge, 1946), Pacifique (Ranson, 1954) est cependant troublante. Au dernier congrès Inqua (Rome-Pise 1952) de nombreux auteurs ont signalé un peu partout dans le monde un mouvement négatif de 2 m. Il semble que les encoches de la Mer Rouge trouvent leur origine dans cette *baisse de niveau mondiale*, bien que nous ne puissions nous prononcer sur le mécanisme qui l'a provoqué.

Par contre, les observations en plongée n'ont pas permis de préciser la question des niveaux ennoyés. Il m'est actuellement impossible de conclure, quant aux récifs que nous avons visités à l'existence de plate-formes d'érosion ennoyées.

En résumé on peut différentier d'une part des mouvements liés à l'équilibre tectonique des compartiments du graben de la Mer Rouge, et d'autre part des changements de niveaux de faible amplitude qui se résument en un mouvement négatif de 2 m et semblent affecter toutes les mers du globe.

STRUCTURE DES RECIFS

I. *Récifs typiques de la Mer Rouge*

1. *Shelf Atolls*: Ils sont rares; nous n'en connaissons que 2 exemples: Sanganeb et le Récif Vert au large de Port Soudan.

2. *Récifs Frangeants*: Ils bordent presque sans exception toutes les côtes, matérialisant la limite de la plaine côtière aussi bien du côté africain qu'arabe. Leurs accores tombent souvent très profondément (500 m). Une telle structure, extraordinaire

pour des récifs frangeants, s'explique par l'ennoyement progressif des compartiments du graben qui les supportent. Ils ceinturent également les îles.

3. *Patés coralliens*: Des masses coralliennes sans structure bien définie (Shoal reefs) encombrent toutes les zones de profondeur inférieure à 100 m. Les madrépores essayent de coloniser tous les substrats qu'ils rencontrent. Relativement peu nombreux sont les édifices qui atteignent la surface. Il en résulte des constructions désordonnées, informes, sporadiques. Nous en avons de beaux exemples sur la plate-forme 60-80 m du Banc Farsan Nord.

4. *Récifs tabulaires*: Le trait le plus caractéristique de la Mer Rouge est la fréquence des pitons coralliens colonisant la plateforme 500-900 m, de part et d'autre de la fosse centrale demeurée libre.

Ce sont des *récifs tabulaires** à sommet plat affleurant et dépourvu de lagon. On peut distinguer 2 variétés: d'une part des récifs à forme plus ou moins circulaire portant parfois une caye de sable (Marmar, Malathu), d'autre part des crêtes allongées sur plusieurs milles, orientées approximativement dans le sens des fractures de la Mer Rouge (type Shab Suleim).

On notera l'extrême raideur de leurs parois. En effet la pente de leurs accores, souvent supérieure à 60°, approche parfois la verticale. A Malathu les accores tombent verticalement jusqu'à – 200 m, certains pitons de l'archipel Souakim présentent des tombants verticaux jusqu'à – 600 m. Comme dans d'autres mers intérieures cette verticalité semble liée à l'absence de marées.

5. Des structures complexes, comprenant des *récifs quaternaires soulevés* englobés dans des récifs plus jeunes prennent place sur les compartiments externes du graben. Ces compartiments dont certaines parties sont immergées, se seraient soulevés sous l'impulsion de poussées tectoniques récentes, entrainant avec eux les récifs qu'ils portaient (Abulat, îles Farsan, Kamarane). L'immersion n'étant pas totale des formations coralliennes nouvelles (récifs frangeants ou barrières) enveloppent ces anciennes structures.

II. *Profondeur de croissance des Madrépores*

La profondeur limite de vie des madrépores est d'une importance capitale dans l'interprétation des théories de formation des récifs coralliens. De nombreux travaux ont été consacrés à ce sujet et les auteurs indiquent en général 60-80 m comme limite inférieure de développement des coraux (Kuenen, 1947). Ces opinions sont basées sur l'examen des résultats de dragages et vérification de l'état de vie des madrépores ainsi ramenés.

Nos recherches en scaphandre autonome ne concordent pas parfaitement avec ces conclusions.† A partir de la surface les vingt premiers mètres sont incontestablement le domaine d'expansion et de croissance des madrépores. Les colonies sont très vigoureuses et bien développées: on assiste à un débordement de formes construites. C'est dans cette zone que la faune associée est la plus dense; plus profondément elle se raréfie rapidement. C'est aussi la zone que visitent les prédateurs pélagiques.

Entre 20 et 40 m les madrépores s'affaiblissent rapidement; à partir de 40 m les

* " Platform reef " de Fairbridge (1950).

† On notera que ces observations se sont appliquées a des récifs en conditions de vie optimum, bien disposés du point de vue du renouvellement des eaux les baignant.

les colonies vivantes sont de plus en plus rares; de larges espaces morts recouverts d'algues calcaires, d'alcyonnaires, d'éponges, de bryozoaires les séparent. A 50 m les colonies vivantes sont déjà une exception et au delà de 60 m on n'en trouve pratiquement plus de sorte que la zone dans laquelle les madrépores peuvent effectivement construire descend jusqu'à 40 m. Ce chiffre serait une limite supérieure. Dans bien des cas il faudrait peut-être dire 30 m. En dessous de 40 m les efforts constructifs des madrépores ne donnent plus de résultats efficaces. Les *encroutements* d'algues calcaires, bryozoaires, etc., qui les remplacent en sont la meilleure preuve. Ces encroutements sont identiques à ceux qu'on rencontre aux mêmes profondeurs en Méditerranée*; c'est le faciès biocoenotique correspondant à ces profondeurs. Dans les mers chaudes et jusqu'à une certaine profondeur ils sont masqués par les constructions madréporiques, bien plus rapides et volumineuses. Mais en dessous de 40 m une grande partie des madrépores sont morts, et les encroutements, reprenant leur place, les recouvrent de leur linceul.

III. *Théories de formation des Récifs*

Les observations en plongée m'ont amenées à admettre 40 m comme *limite inférieure de construction* pour les madrépores. Dans cette limite de profondeur et dans des conditions favorables (eaux chaudes, bien renouvelées, etc.) les madrépores colonisent tout substratum qui s'offre que ce soient les rochers de la côte, des hauts fonds sous-marins, ou des récifs du large en voie d'ennoyement. Ceci a conduit les auteurs modernes à adopter de plus en plus des théories synthétiques et a expliquer les récifs d'une même région simultanément par plusiers théories (FAIRBRIDGE, 1950). Il en va da même en Mer Rouge. Les collines non coralliennes des Dahlaks ont été couronnées de récifs coralliens alors qu'elles étaient faiblement immergées(CROSSLAND, 1907). Les zones peu profondes ont vu fleurir les pâtés coralliens. Mais la grande majorité des côtes s'approfondit brutalement et les zones peu profondes sont statistiquement de faible importance en Mer Rouge. Nous nous trouvons dans une région de graben, dont les compartiments ont non seulement joué depuis le tertiaire mais jouent encore actuellement. Tous les pitons, et une grande partie des bancs coralliens sont enracinés dans des zones profondes sur la plate-forme 500-900 m.

Ceci m'a conduit à admettre que la *subsidence* est statistiquement le facteur le plus important dans la formation des coraux de la Mer Rouge.

Cette conclusion n'exclut d'aucune façon la superposition d'un glacioeustatisme quaternaire, mais celui-ci n'aurait exercé dans la plupart des cas, en Mer Rouge, qu'une action morphologique sur des récifs préexistants.

DEVELOPPEMENT DES RECIFS CORALLIENS

L'observation en scaphandre autonome, au cours de nombreuses plongées sur tous les types de structures, à tous les niveaux, vers le large ou sous le vent, m'a permis de mettre en relief certains faits.

I. *Erosion*

On peut classer les phénomènes d'érosion marine en 3 gruopes: actions mécaniques, physico-chimiques et biologiques.

* Ce sont les fonds dit "coralligènes" de MARION (1883).

1. Les traces d'*érosion mécanique* sont rares en Mer Rouge. Il n'y a pas de typhons et les houles de tempête ont peu de possibilités de s'éxercer. On ne rencontre que de rares levées de galets formées des branches des colonies brisées par les vagues.

2. Je n'ai pas observé de preuves d'érosion purement *physico-chimique*. Sous l'eau on ne rencontre jamais de formes de dissolution. Hors de l'eau la quasi absence de précipitations atmosphériques empêche le développement des karsts. Tout au plus pourrait-on observer des phénomènes d'alvéolisation par des embruns dans les zones situées au dessus des encoches littorales.

3. On rencontre plusieurs formes d'*érosion biologique*. Les organismes perforants semblent jouer un rôle secondaire. On ne les trouve que sporadiquement et ils ne pénètrent que dans la couche superficielle (10 à 15 cm) des colonies.

Les poissons, surtout ceux appartenant aux groupes des: Peroquet, Diodon, Baliste sont très actifs. Ils " broutent " les colonies vivantes, arrachant à coups de bec des lambeaux de la couche superficielle des madrépores. Après broyage les particules calcaires sont rejettées alors que la matière organique est assimilée. Ces débris sont à l'origine des sables coralliens. Les fractions les plus fines, entrainées plus facilement par les courants, vont former les boues coralliennes des lagons.

De petites algues Cyanophycées, selon Ercegovic (1932) et Frémy (1945) seraient responsables de certaines formes d'érosion cantonnées dans la zone intertidale et un peu au dessus: rainures littorales, rochers champignons, lapiés et plateformes d'érosion. Ces algues, susceptibles de secréter des acides, creusent de minuscules cupules dans le calcaire. A la longue, ces cupules, se recoupant, érodent la roche. Il semble que ce soit bien le cas en Mer Rouge où j'ai observé de telles cupules encore occupées par des Cyanophycées. Ce phénomène est général, on le rencontre dant toutes les mers, en particulier en Méditaerannée où j'ai effectué des observations analogues.

Ainsi les phénomènes d'érosion en Mer Rouge sont assez restreints. L'activité des poissons broutant le corail produirait les sédiments coralliens, celle d'algues attaquant le calcaire nous conduirait aux formes d'érosion littorale: encoches, lapiés, etc.

II. *Colmatage*

Les sédiments meubles (sables, craies) se déposants sur toutes les parties des récifs comblent les vides laissés par les formes construites. Après consolidation ces zones font masse avec les parties construites. Nous ignorons actuellement comment se produisent ces phénomènes de consolidation.

III. *Beachrock*

J'ai attribué la formation des *beachrocks* de la Mer Rouge à l'activité bactérienne. En effet le premier dépôt qui saisit les sables de plage est un voile de calcaire qui semble amorphe. Ce premier dépôt cristallise au bout d'un certain temps en aiguilles d'aragonite, qui instables, recristallisent en rhomboèdres de calcite. C'est ce stade final qui est le plus souvent observé. En appliquant la méthode (Nesteroff, 1955) que j'ai récemment mise au point pour la recherche de l'origine d'un dépôt calcaire j'ai trouvé dans ce premier voile une trame organique bourrée de bactéries. Une telle trame caractérise les dépôts dus à une activité bactérienne.

IV. *Evolution des récifs*

Certaines formes récifales m'ont paru difficiles à expliquer par les causes d'érosion dont j'ai pu observer l'action: lagons avec leur pinacles, les passes des atolls et des récifs barrières, les irrégularités, entailles et cavernes des accores. L'action des Cyanophycées, importante surtout dans la zone intertidale, les poissons fabriquant des débris mais incapables d'une action de sculpture, l'absence en général d'érosion sous marine m'ont conduit à attribuer ces formes à une *croissance différentielle* des madrépores.

Je suis ainsi conduit à penser que tout récif de la Mer Rouge est la résultante de phénomènes de croissance et de colmatage. Les madrépores tentent d'atteindre la surface. Lorqu'ils y parviennent, toute croissance verticale est stoppée. Les colonies d'un accore ne peuvent se développer que latéralement. Cette poussée latérales se produit de préférence vers le large, et non vers le lagon dont les conditions sont moins favorables au développement des madrépores. On imagine facilement que lors d'une subsidences les accores d'un récif aient tendance, si le substratum le permet, à migrer vers le large, à agrandir la périphérie du récif, abandonnant au centre un lagon de plus en plus vaste. Ce serait peut-être la l'éxplication de certains atolls. Dans cette théorie de *migration latérale des faciès* le premier stade d'un atoll ne doit pas nécessairemet être un récif frangeant un île ou un cône volcanique. Toute autre forme peut convenir.

SEDIMENTATION

1. *La boue blanche a Foraminifères*

Dans la région nord des Farsans, nous pouvons distinguer un type très général, planctonique, de sédimentation. Il caractérise la plateforme 60-80 m. L'influence du continent n'est pas sensible, même le long des côtes.

Il s'agit d'une boue blanche à Foraminifères et Ptéropodes. Parmi les Foraminifères, les Globigérines sont de loin les plus nombreuses. Ces divers organismes forment plus de la moitié du sédiment (55%), la fraction fine n'est pas identifiable.

On trouve cette boue à Foraminifères par 80 m de fond. Ainsi ce sédiment n'est past nécessairement lié à des conditions de profondeur comme le croyaient les auteurs anciens. Elle cractérise ici l'absence d'apports terrigènes et coralliens.

2. *Sédimentation Récifale*

Les zones récifales tranchent sur la sédimentation générale (pélagique) du Banc Farsan. Les récifs frangeants côtiers ou pâtés coralliens sont des mondes quasi fermés ayant leur vie et leur évolution propre. Chacun de ces récifs introduit une zone de sédimentation bio-détritique.

La grande masse de ces sédiments coralliens est constitué de sables et de boues calcaires. Les sédiments grossiers sont peu fréquents et les levées de galets rares. A l'exception de ceux des plages, les sables coralliens sont des *sédiments par densité.* Il faut chercher leur origine, d'une part dans les débris rejetés par les poissons qui broutent le corail et d'autre part dans les tests de la faune associée aux madrépores, tests qui tombent au fond après la mort des animaux. Ces tests et débris forment un éboulis que l'on retrouve au pied de toutes les structures, accore ou paté de corail. Ces formations sont l'équivalent des éboulis de pied de tombant en Méditerranée. Dans les deux cas, au milieu d'une sédimentation fine, des conditions

locales (falaise sous-marine en Méditerranée, tête corallienne en Mer Rouge) introduisent des apports plus grossiers.

Les fractions d'étritiques les plus fines, entraînées par les courants forment les boues coralliennes qui se rassemblent dans les lagons. Vers de large elles sont rapidement masquées par les dépôts pélagiques, statistiquement plus importants.

Une très faible valeur des apports terrigènes caractérise la Mer Rouge. Dans les récifs du large elle est inférieure à 1%, dans les frangeants côtiers elle ne dépasse pas 1,5%. Le manque de précipitations atmosphèriques, ainsi que la rareté de vents traversiers (E-W) semblent responsables de ces valeurs.

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Laboratoire de Géologie Marine de la Sorbonne, Paris.

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LETTERS TO THE EDITORS

Direct measurements of sub-surface currents

PROFESSOR K. F. BOWDEN's valuable review (*Deep-Sea Research* 1954, **2**, pp. 33-47) of direct measurements of sub-surface currents in the oceans focuses attention on what many oceanographers will agree to be the primary task of observational oceanography: to delineate the major features of the ocean circulation, not only at the surface, but also beneath it; to construct charts of the mean distribution of velocity at all depths; to discover and describe the fluctuations from this mean, be they tidal, annual, or irregular. The traditional means of making observations of current velocity is an indirect one, the so-called dynamical method, based on highly precise measurements of temperature, salinity, and depth, the hydrographic tables for computing density, the geostrophic equation, and an assumption regarding the depth of no motion. The uncertainty involved in the latter assumption has not been resolved, and so even the mean sub-surface current charts are highly speculative. The description of the distribution, periods, and even existence of large scale fluctuations in sub-surface currents has not been achieved in any sense at all. The possibility that short period variations in deep circulation may occur, and yet be quite undetectible by dynamic computation has already been pointed out by ROSSBY on theoretical grounds (*J. Mar. Res.* 1937-38, I, **3**, pp. 239-263). It is certain that the dynamical method alone must leave us short of our goal, but if we can find an alternative method of current observation that will help eliminate some of the uncertainties inherent in the dynamic method, we will then be in a position to reap a rich harvest indeed from the great quantity of hydrographic data already accumulated.

Although the number of direct measurements is presently very small, as Professor BOWDEN points out, it seems to this writer unduly pessimistic to suppose that it will always be so. The purpose of this letter is to discuss a possible future programme of observation which could provide a very large amount of information on sub-surface currents.

The extensive and remarkable developments in the field of underwater sound made during World War II, notably by Dr. M. EWING's invention of *Sofar*, have now placed in our hands the means of making continuous day by day measurements of currents on a permanent basis, so that we should eventually be able to plot synoptic charts of the currents at various depths in much the same way as meteorologists keep abreast of the winds. For a variety of reasons *Sofar* is far superior to radio or radar for these purposes.

In the discussions at the Convocation in June 1954 at the opening of the U. S. Navy Laboratory of Oceanography at Woods Hole, it became clear that the basic instrument required is the oceanographic equivalent of the meteorological constant altitude balloon: an unmanned sub-surface buoy or float, devised so as to float at a nearly constant depth, or along an isopleth of temperature of density, and equipped with a clockwork designed to drop and/or fire *Sofar* charges at certain predetermined times, say once a week, for periods up to half a year.

At least two possibilities for the design of such an apparatus come to mind: (1) the float might contain batteries and a small pump to keep itself in "trim" in the manner of a submarine, or (2) a buoyant float, made of a material less compressible than water, might be made to operate satisfactorily without any power-driven ballast control. The second method is more economical, more elegant, and correspondingly more difficult to design: for example, provision for releasing a small auxiliary float with every bomb would be necessary to keep the parent float in trim. The trajectory of each buoy could be determined from the times of arrival of the explosive sound wave at three *Sofar* stations. At least two groups are at present planning to develop such a device, and if it proves feasible, the way will then be clear for a major advance in physical oceanography.

In the North Atlantic there is already one *Sofar* station at Bermuda, maintained by the Lamont Geological Observatory. Two other *Sofar* stations should be set up: one, for example, at Fayal in the Azores, and another at Puerto Rico. The *Sofar* fix requires three monitoring stations. They are not very expensive installations and the two additional ones could be run with a very small

staff. The *Sofar* fix is quite accurate, so that tidal currents of about 10 cm/sec could be detected, whereas, for slow drifts, currents as slow as 10^{-2} cm/sec could be detected.

Probably the easiest way to maintain a constant observing programme would be to release the sub-surface floats from weather ships at regular intervals, and in groups arranged to float at predetermined different depths. One way to distinguish one signal from another would be on a basis of time – the bombs could be fired by clockwork. The three stations could be used for regular air-sea rescue work.

It seems to the writer that *Sofar* time bombs are the only practicable technique available. Anchored and moored current recorders are subject to the relatively large tidal currents and perhaps also to turbulent irregularities in flow, both of which will tend to mask the slow mean drift which, of course, is one of the quantities we want to measure. Following submerged floats by ship is very expensive, and hence would not be used widely or continuously enough to provide long term records. Clouds of dye or radio-active material diffuse too rapidly to be really useful and also require ships. Radio-direction-finding or loran repeater techniques for locating buoys require surface buoys and antennas exposed to the wind. The *Sofar* technique is free of these objections. Its chief drawback is the limited number of bombs a single float can carry, and hence the limited number of fixes available for any one buoy.

It is possible that deep currents are very steady and broad, in which case direct comparison of the observed trajectories with the mean dynamic topography will be very illuminating. However, it is also possible that deep currents are characterized by narrow regions of high velocity, with broad expanses of weak and variable velocity, and that there are fluctuations in the deep circulation associated with storms, or with more prolonged disturbances of the wind systems over the ocean, or even with seasonal wind changes. If so, it will be very difficult to observe the accompanying changes in the density structure (dynamic topography).

Perhaps in the next few years we will find direct measurements of currents in the deep ocean to be relatively easy, but that adequate observation of changes in the density field will present the most serious difficulty. Ships, of course, cannot be used economically. Any attempt to maintain a large scale net-work of moored telemetering buoys for monitoring temperature and salinity fluctuations would be elaborate and expensive, although maintenance of a few buoys at critical locations might be feasible. Whether periodic serial observations by weather ships would give sufficient data is questionable. Observations by thermometric cable, such as the one at Bermuda, are limited in scope because there are so few mid-Atlantic islands. Thus the present indications are that the future of direct current measurement in the deep ocean is a very bright one, but that the observation of accompanying variations in the density field will be considerably more difficult. A permanent current observing programme of this sort could be a basis for international cooperation in Atlantic oceanographic observing programmes.

HENRY STOMMEL

Bermuda, 1 *January*, 1955.

A plea for Oceanology

(*Received* 24*th June*, 1955)

DR. CARRUTHERS seeks to defend incorrect terminology on the grounds of " custom and long usage " – surely a reactionary argument.

The vehemence with which he rises to my challenge serves to emphasize the extent to which the real meanings of words have become corrupted. Thus, if Biology means the Study of Life, what else but a particular facet of it is Biography – the Description of a particular Life ? So with Geology, literally the Science of the Earth ; is not a geographer basically one who maps its surface, draws it, or describes it ? Again, Hydrography plainly connotes the Charting of Waters, a singularly apt definition for my profession. Our members, though, would hardly claim more than a superficial knowledge of Water ; that science is, or should be, the province of the hydrologist.

The purpose of my letter was to draw attention to the corruption and confusion of words and to plead, in the interests of progress and understanding, for the adoption of terms appropriate to their literal meanings.

If, as Dr. CARRUTHERS suggests, I am flogging dead horses, then there can be no hope. I submit, Sir, however, that not all the horses are dead – oceanographers, for example, have still a future before them. To rationalize their designation is surely one of the simpler hurdles that confront them, and if they shy from this let us hear no more of the water-logged course and the heavy going.

Because he is a thoroughbred the Oceanologist will attract the young rider and win through ; the Oceanographer will bring up the rear, for in truth he is but a draught-horse.

G. P. D. HALL, Commander, R.N.

Hydrographic Department (Admiralty)
Oxgate Lane,
Cricklewood, London, N.W.2.

Book Review

Dynamical Oceanography. J. PROUDMAN. pp. 409. Price 55*s*. Methuen & Co. Ltd.

AN INTERESTING and lucid text-book will often attract a student into a subject which might otherwise remain unknown to him. Dynamical oceanography has in the past attracted few specialists and up to now it has had no textbooks in English. It is a composite subject with workers studying various isolated fields which could properly be classified under one or other of the classical headings in physics and chemistry. The investigation of individual topics will obviously remain the rule but there is apparent a focus for all workers in the field. It is that they must at all times formulate their problems with the ' real ' ocean in mind. This will make them reject ideas which might otherwise be tenable. It is hard to express this concept but therein lies the justification of the term oceanography rather than marine Chemistry or hydrodynamics.

This feeling is present in Professor PROUDMAN's book – he is dealing with the application of dynamical principles to the ocean and, although the argument is carried on in parts by 'type-problems' in which cause and effect are investigated without the cause necessarily being representative of conditions met in the ocean, he does, by numerous examples taken from data gathered by oceanographic expeditions, point to what is important and what is not. The book certainly fulfils the need expressed in the first paragraph above – it is interesting and lucid although perhaps it sacrifices a certain amount of elegance to achieve this. We are taken back in each chapter to basic principles from which the relevant expressions are constructed. We *are not* presented with the general equations of motion from which various terms are omitted. We *are* told of the forces acting on such and such a mass of water and the accelerations which balance them. The result is of course the same but there is a certain simplicity of approach which is refreshing.

Professor PROUDMAN, being the first in the field, has had to set his own pattern. In the early chapters he examines in detail the terms that will be used throughout the book – gravity, density as determined by temperature and salinity, pressure and accelerations including those due to the rotation of the earth. These last play an important part in motion in the sea, for unaccelerated frictionless motion on the rotating earth is at right angles to the pressure forces instead of in the direction of the forces as they would be if the earth was not rotating – a profound modification.

Thereafter most of the chapters are concerned with cases where one or other of the forces that could act on the water predominates over the others. Thus first friction and acceleration relative to the earth are neglected and gradient or geostrophic currents are discussed and worked examples included. Then the concept of turbulence is introduced in a simple manner although at the expense of rigour. It is finally formulated in terms of ' eddy ' coefficients of viscosity which express the turbulent transfer of momentum in relation to the mean flow. This is the form required in the later chapters as the turbulent motion is not itself discussed. The large magnitudes of the eddy coefficients compared with the molecular ones makes all the difference to, for example, the surface motion of water as developed by the wind. This is all discussed, again with examples.

In the closing chapters of the book accelerated motions are considered. These are, to quote two cases, seiches in lakes and perhaps the most obvious motion to the world at large – the tides. On this subject the author is the authority and perhaps it is here that his ability to teach us is clearest. Notwithstanding the complicated problems on which he has worked, he passes on to us in a simple manner the ideas of tide generating forces and the modifications resulting from shallow water effects and pressure disturbances.

There is one other chapter which deals with a question that is certainly of the greatest importance but about which discussion has been largely qualitative. This is the effect of thermodynamical considerations, which are after all basic to the circulation in the ocean in so far as the energy originates, apart from gravitation, in solar radiation. The book gives an interesting qualitative argument to explain the meridional circulation of water on a large scale between the cold poles and the tropics.

Each chapter, although in general self-contained, does refer back many times to points of interest in other chapters and this may be a slight hindrance to easy reading if they are followed implicitly. There are many simple diagrams to illustrate the text and one can find ones way about the book quickly with the aid of a good index.

Perhaps in later years, when the science of physical oceanography is not quite so new, we may have a presentation in which, instead of isolating elements that appear to be of importance in any specialised area, the motions in the sea are treated as a unified whole. This will in a way be a return to physical oceanography as carried on for many years in the past through the observational study of large areas of the ocean but this time founded on quantitative theory. Until then we must pursue in the manner of Professor Proudman our individual problems so that we may achieve a full understanding of the physics and mathematics essential to this next stage. In this advance Professor Proudman will have helped us greatly by giving us this guide.

J. Crease

OBITUARY

Dr. G. M. Lees, M.C., D.F.C., F.R.S.

Dr. George Martin Lees, who died on 25th January, 1955 was not only one of the outstanding oil geologists in the world, but also through his interest in the formation of the earth's crust, was a stimulating contributor to the study of the floor of the oceans. Although he died at the early age of 56 George Lees had lived a very full life. Of Scottish descent he was brought up in Dublin, until, at the age of 17, he entered the Royal Military Academy at Woolwich and in the following year was awarded the Military Cross while on Active Service with the Royal Artillery in France. A transfer to the Royal Flying Corps led to a tour of duty in Egypt and Mesopotamia, where he earned the Distinguished Flying Cross for exploits behind the Turkish lines, not far from the position of the present great oilfield at Kirkuk. A two year appointment as Assistant Political Officer in Iraq, where he lived an adventurous life in the mountainous district of Southern Kurdistan, started Lee's interest in geology, and in 1920 he entered the Royal School of Mines. He cut short the course to join the Anglo-Persian Oil Company, and after a few years in which he made the classic surveys of South-West Persia, Iraq and the Oman Peninsula, he supplemented his academic training with a period of study at Vienna during which he gained his Ph.D. with a thesis on the geology of the Oman mountains.

In 1930 Lees was appointed Chief Geologist of the Anglo-Persian Oil Company and he held this post for 23 years, during which time he travelled extensively and frequently. During these travels he became acquainted with the major mountain regions of the earth. The combination of a good eye for tectonics and great experience of structural geology obtained from ground observation and from oil-well drilling, together with the fact that Lees covered probably more territory per year by air than any other geologist, led to a firm belief in the similarity of the geology of continents and oceans. While this belief was not in accord with the views of all geophysicists it did make for some most amusing and provoking joint meetings and discussions and Lees could always be relied on to state a lucid geological case and to confuse and refute the geophysical arguments. He did, of course, realize the value of geophysics, and had for many years seen the potentialities and limitations of the various methods in Persia. He showed great interest in all underwater geophysical work, and by his queries and suggestions assisted greatly in a true appraisal of the meaning of the results of this type of work.

After his retirement from the Anglo-Iranian Oil Company in 1953, Lees was able to carry on his interest in fundamental geological problems, which he had expressed in his two Presidential Addresses to the Geological Society. He had hoped to contribute to a discussion on the origin of the Earth arranged jointly between the Geological Society and the Royal Astronomical Society, but the meeting was held the week after his death.

It is a sad thing that Dr. George Martin Lees should have died so young, with his mind actively employed on the many pursuits that were his. Those who have walked the hills with him in post-war years are especially mystified at the workings of fate, for he was the young man of any party, both in physical strength and mental keenness. He was always first to the top of the Kuh.

T.F.G.

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